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EMERGED PHOSPHATE ISLANDS IN MICRONESIA

BY L. E. NUGENT, JR.

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ABSTRACT

Eight small emerged atolls or lagoonless coral islands in Micronesia have phosphate deposits: Minami Daito, Kita Daito, Okino Daito, Marcus, Angaur, Fais, Nauru, and Ocean. Two of these have exceptionally well-preserved rims, one lagoon evidences considerable filling, several are cliffed, seven lie in stable zones, and six have low-level abrasion benches. The islands range from the equatorial zone to the marginal zone. The presence of phosphate deposits, and paleontologic and geomorphic evidence indicate that the rims and uplands are pre-Wisconsin. While the low-level abrasion benches in the equatorial as well as in the marginal zone corroborate the Glacial Control theory, the fact that such small islands have survived truncation apparently attests to the inefficacy of wave abrasion.

INTRODUCTION

Of the thousands of islands in the western Pacific only Guam and the Philippines were reasonably well known by American geologists prior to the war. The economic

insignificance of Micronesia, the remoteness, and the obstacle presented by Japanese isolation of the mandate all served as effective deterrents to thorough geologic investigation. Antithetically, however, the war resulted in an accumulation of basic data vastly incommensurable with the relative consequence of the islands; the photographic coverage by the Armed Forces and the meticulous hydrographic surveys of the Japanese Navy present these islands more accurately and minutely than the surveys of most of North America.

Although many questions still remain, the new data indicate that eight "phosphatic" islands in Micronesia are apparently emerged atolls or lagoonless coral islands: Minami Daito Jima, Kita Daito Jima, and Okino Daito Jima between Kazan Retto and Nansei Shoto; Marcus, northeast of the Marianas; Fais and Angaur in the Carolines; and Nauru and Ocean, west of the Gilberts (Pl. 1.).

In spite of the fact that all have emerged until the lagoon floors or reefs are above sea level, these islands manifest considerable diversity. Two have well-preserved rims, three only remnants. One lagoon evidences considerable filling, two none. The islands range latitudinally from the equator northward beyond the present limit of luxuriant coral growth. Several lie outside the Yap and Mariana arcs in the so-called basaltic province, and several within the arcs in the andesitic province. Seven lie in stable zones, and one on a small island arc. Further, offshore gradients vary from normal to unusually gentle.

As expected, little has been written on these islands by American geologists. In the *Coral Reef Problem* Davis (1928) sketchily discussed all of them. Under the subheading *Elevated Atolls in the Western Pacific* (p. 419), in which seven were mentioned, he strangely included Guam as an elevated almost-atoll in spite of the fact that he classified the adjacent, and similar, coral terrace islands in the Marianas (Rota, Aguijan, Tenian, and Saipan) as elevated reefs. Hobbs (1944, p. 243, 246) briefly described Fais and Angaur, classifying both as elevated atolls; because of a lack of soundings he inadvertently placed Fais within rather than without Nero Deep. The present writer (1946, p. 765) mentioned Fais and Angaur in a discussion of the Caroline group.

While a number of Japanese papers on the mandate were published prior to the war, those recently abstracted by Gardner (1946, p. 22–48) have proven of exceptional significance, especially as regards the age of various elevated coral limestones. Moreover, the core hole on Kita Daito Jima provides information second to none.

Mensuration is based on the nautical mile (6080 feet). Depths are fathoms. All charts referenced are United States Navy Hydrographic Office charts.

ACKNOWLEDGEMENTS

The writer is greatly indebted to Dr. H. S. Ladd who reviewed the manuscript and made a number of valuable suggestions. Moreover, great benefit has been derived from discussions with Dr. G. W. Berry. Most of the data were procured while the writer was in the U. S. Navy, when there was ample opportunity for study and comparison of these islands as well as most of those in Micronesia. Chief sources were high and low altitude photography and hydrographic data, the writer having returned

to the United States shortly before the assault on Angaur, the first of these islands to be occupied by U. S. Forces.

MINAMI DAITO JIMA AND KITA DAITO JIMA

Minami Daito Jima (25° 51′ N. Lat., 131° 15′ E. Long.) and Kita Daito Jima (25° 57′ N. Lat., 131° 18′ E. Long.) are the most remarkably preserved elevated atolls in Micronesia. They lie in the northeast trades, north of the Tropic of Cancer, about 200 miles southeast of the Nansei Shoto. Temperature of surface water in February is 21°C. From rather meager bathyspheric data, the islands appear to be located in a stable zone within the andesitic province. Kita is approximately 5 miles north by east from Minami and is separated from it by a saddle somewhat over 800 fathoms deep. Both islands are exceptional in the clarity of their lagoon and rim relations.

Minami, the larger, is 3 by 3½ miles (Fig. 1.) and completely surrounded by a rim that averages slightly over 3000′ wide, the wider portion lying on the east side. The upland portion of the rim is approximately 200′ above sea level and there are no well-defined pass vestiges. On the north and east sides the rim has several coral ridges that apparently reflect slight tilting. There are several low areas and a number of well-developed sinks; although none of the sinks are large in area several approach depths of 100 feet. Phosphate workings are concentrated on the western portion of the rim.

The inboard slope off the rim descends steeply to the former lagoon floor. Although the periphery of the floor is somewhat higher than the center, there is neither evidence of a significant detrital slope, nor a pronounced decrease in declivity toward the toe of the slope, nor any decided variation in the degree of slope from one side of the lagoon to the other. The floor is studded with shallow depressions, probably the result of initial irregularities and solution effects. Although these depressions are apparently of similar size and depth throughout, they are lower and water-filled where the western half of the floor approaches sea level, which may indicate a slight detrital drift from windward or moderate tilting during uplift. It is noteworthy that there are remnants of only one coral head and one coral ridge projecting from the lagoon floor.

The outboard slope is precipitous on all sides. Moreover, there is no fringing reef at sea level nor evidence of vigorous post-Wisconsin coral growth. Apparently in these latitudes ecologic conditions are still unfavorable. In the Bonins (26° N. Lat.) Sugiyama (Yabe and Sugiyama, 1935, p. 210) found that there were few corals on the windward side of the islands and that luxuriant growth occurred only in the protected parts of Futami Ko and other sheltered areas. Cliff formation by wave erosion is well manifested; two, and frequently three, wave-cut benches are easily identified. Although it is difficult to deny categorically any evidence of a normal marginal reef slope, the entire perimeter has apparently been modified by wave action. This conclusion is further affirmed by an unusually well-defined subsea bench that averages about 1500 feet in width along which soundings range to 46 fathoms, the depths expected to accompany wave action during Pleistocene. Beyond the margin of the

bench, depths increase rapidly and the slope is comparable to that of normal atolls in the western Pacific.

Although somewhat smaller, Kita Daito Jima closely resembles Minami in all

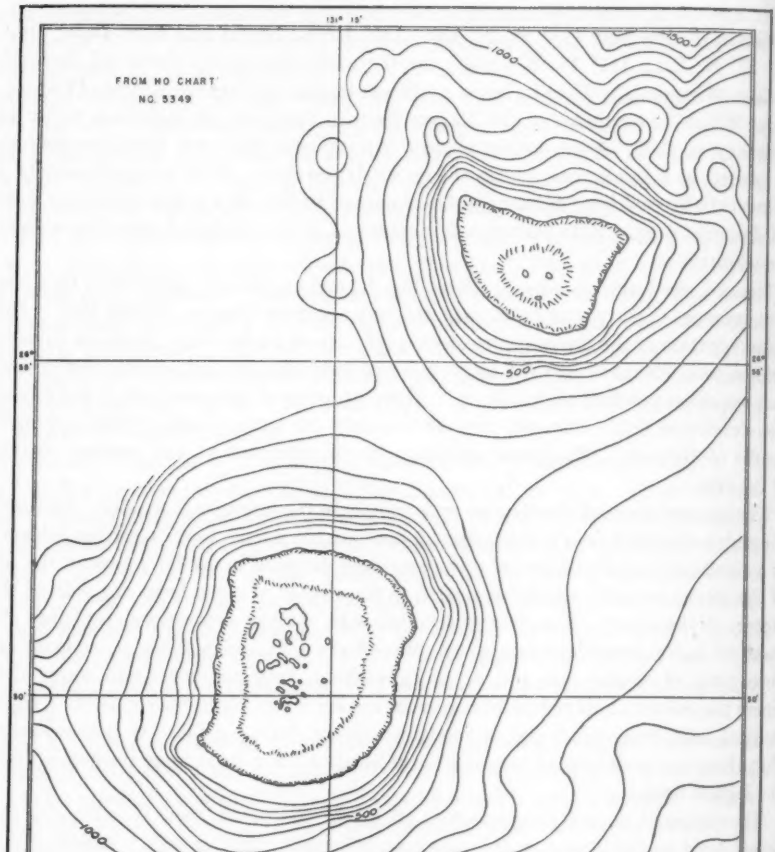

FIGURE 1.—*Minami Daito Jima and Kita Daito Jima*

major aspects (Fig. 1). While Kita's well-developed rim is nearly a mile wide on the east, the windward, side, the remainder is approximately the same as that of Minami. The highest point, the site of much of the phosphate workings, is on the inner margin of the western side and reaches 230 feet. The remainder approximates 200 feet.

The upland rim area is almost completely bounded on both the inboard and out-

board margins by coral ridges; the inner ridge is transected by a pass notch on the southeast side. Between the marginal ridges the rim slopes slightly from both sides toward a medial line, which, in cross section, creates a shallow saddle, and which may indicate unusual similarity of growth at the lagoon and seaward margin. Although the rim is hummocky, probably the result of solutioning and primary irregularities, there are no deep sinks as at Minami.

While the inboard slope is steep along the linear sections, the slope decreases at the sharp re-entrants on the northeast and southeast and tends to grade into the lagoon floor, a relation characteristic of normal atolls. The floor is hummocky and in the central section several ponds lie near sea level. There are no remnants of large coral heads or ridges projecting from the floor.

There is neither a fringing reef nor luxuriant coral growth at sea level. A low near-vertical cliff surrounds the island on all sides, obviously the result of wave action. Above this section the degree of slope lessens to the marginal coral ridge, evidence of either the original marginal slope or modification by wave erosion. As at Minami, the underwater gradient is low and a well-defined peripheral bench approximately 1500 feet wide lies at the depth expected from wave action as a result of eustatic lowering during the Pleistocene. Beyond the bench, submarine gradients are normal.

OKINO DAITO JIMA

Okino Daito has been the most thoroughly exploited of the Pacific islands worked for phosphate. No area of consequence has escaped at least preliminary working, and the surface presents a honeycombed maze of pits and pinnacles as a result of the removal of the enriched rock from the more barren carbonate.

Okino Daito (24° 28′ N. Lat., 131° 11′ E. Long.), 80 odd miles due south of Minami Daito Jima, about midway between Iwo Jima and Formosa, lies in the northern half of the northeast trades and north of the north equatorial current. The temperature of the surface water in February is 22°C.

The island is shaped like a subhedral isoceles triangle with the base but five-eighths of a mile and the altitude 1 mile, in all an area well under half a square mile (Fig. 2). It is surrounded by a narrow fringing reef that is widest on the southeast side. The reef is dead and on the southeast side is slightly above sea level. When compared to reef flats in lower latitudes this flat is exceptionally rough and pitted as well as much darker, all indications of greater antiquity. At the outer margin, especially on the southeast, a windrow of huge blocks of reef debris has resulted from the margin of the reef having been broken off and washed up by storm waves. Similar relations have been observed at Eniwetok (Stearns, 1945a, p. 783–788) and elsewhere in lower latitudes, but the volume of debris in no way compares to that at Okino Daito.

An inner fringing reef lies 10 feet to 20 feet above sea level and, again is widest on the southeast side. This reef flat is very dark and apparently none of the level initial surface remains. Moreover, the seaward margin is excessively crenulate with many re-entrants cut back almost to the inner periphery. Evidently the effects of solution and erosion have advanced far toward total destruction.

Although the fact that both emerged reefs are roughly the same height above sea

level on all sides of the island suggests that the two stages may have resulted from eustatic variation, the slight tilting perhaps favors elevation of the seamount. Stearns' (1945b, 1071–1078) studies on eustatic levels have showed plus stages at 22, 27, and 45 feet.

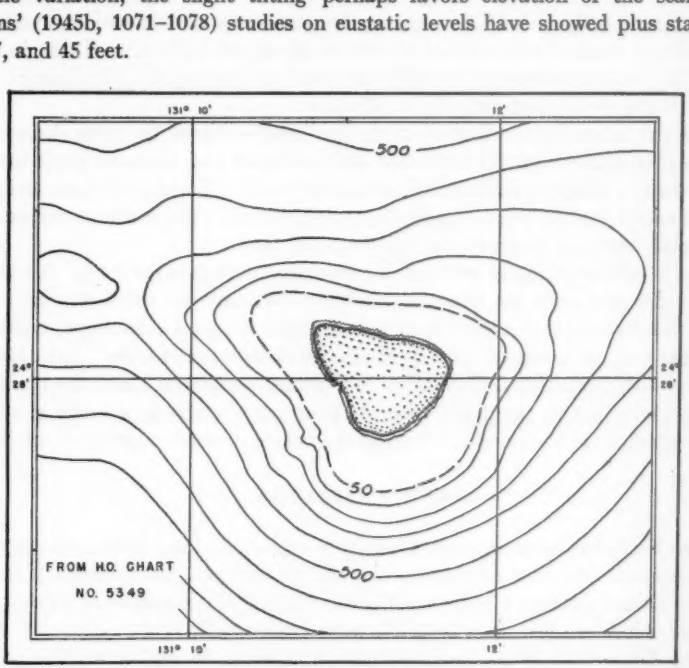

FIGURE 2.—*Okino Daito Jima*

As Minami and Kita, Okino Daito is surrounded by a subsea bench that is especially emphasized because of the ratio of bench to island area. The bench lies at the depths prescribed by eustatic lowering during the Pleistocene and, although the width is about 2000 feet off the northwest, the average is approximately 1500 feet.

While the periphery within the upper fringing reef shows the effects of considerable erosion and solution, the island is bound by a wave-cut cliff up to 50 feet high except on the east and west points where there are gentle declivities. There is no sharp well-defined rim and lagoon as at Minami and Kita; no evidence of an outer marginal reef slope exists and that of an inboard slope is ill defined. Nonetheless, a central depression a few feet lower than the 100 feet reached by the outer belt opens toward the eastern point where a secondary depression is found. The central area is the site of the most intensive phosphate workings; several large pits approach sea level.

MARCUS ISLAND

Marcus Island (24° 18′ N. Lat., 153° 58′ E. Long.) is in the same relative latitude as Iwo Jima and about 700 miles east of it. Marcus lies in the northeast trades and

the temperature of the water is similar to that at Okino Daito. Marcus is triangular, the base and altitude each about $1\frac{1}{4}$ miles. From a hydrographic survey in 1902, Bryan described Marcus as a raised atoll with a maximum elevation of 75 feet and with the outer slope marked by six beach lines, thus indicating intermittent emergence.

Although no modern hydrographic survey is at present available, excellent aerial photographic coverages were procured by the Navy before the surrender. The island was so completely altered by the Japanese in the extensive fortification and the construction of a two-strip air facility that evidence of beach lines has been frequently obliterated and that of phosphate mining largely obscured. Gentle declivities join the beach to the slightly elevated upland that contains only a very shallow central depression, perhaps in part the result of phosphate mining. There is no well-defined rim as at Minami and Kita; it is manifestly less even than at Okino. In many respects the island more nearly resembles a slightly emerged lagoonless coral island than an elevated atoll. The fact that bomb craters in the central area were frequently partially water filled indicates that the island is lower than Bryan estimated because the water table undoubtedly is but a few feet above sea level throughout most of the year.

Marcus is surrounded by a fringing reef that averages 1200 feet wide on the northwest side, 600 feet on the east, and less than 500 feet on the south. These reef widths are anomalous when compared with the atolls of the western Pacific because reef growth is ordinarily more rapid to windward than to leeward. The reef at Marcus, as at Okino Daito, is evidently all dead and the dark tones suggest considerable age. Moreover, the eastern and southern sections have been deeply incised by wave action and reef blocks have been strewn on the marginal edge by storm waves. There is little evidence of the characteristic tooth structure at the marginal slope that is common in lower latitudes. Thus, the windward reef may have been wider than the leeward during the period of growth and the vicious wave attack to windward may have reduced the dead reef to its present width. Although the hydrographic chart contains no soundings, Bryan reported shoal waters around the island and these can be clearly seen off the eastern and northern points on aerial photographs, facts that tend to sutstantiate the suggestion of reef antiquity and wave planation.

ANGAUR ISLAND

Palau arc is approximately 100 miles long and lies concentrically within a trough over 4450 fathoms deep. The arc is south of 10 degrees North Latitude and lies at the heat equator in the summer. In the winter the islands are in the northeast trades and the north equatorial current; in the summer in the doldrums and counter equatorial current, particularly marked physical variations because of the proximity of the Asiatic landmass. Throughout the year the surface temperature of the water is above 27°C.

Since Semper's treatise (1881), the Palau Islands have been frequently discussed from the viewpoint both of petrology and of reef relations. Hobbs (1944) and the present writer (1946, p. 772–774) have recently considered these phases. Tayama's

reports (1939; Gardner, 1946, p. 34–37) comprehensively treat Babelthuap. This considerable literature has resulted from the several anomalies presented by the group: the bauxite deposits; the uplifted reefs on the southern islands, some over 600′ high; the reef masses on the volcanic island of Babelthuap; the mile wide barrier reef to leeward; and the drowned atoll (Velasco Reef) and faroes on the northern end of the arc.

Angaur Island (6° 55′ N. Lat., 134° 9′ E. Long.), the southernmost island on the arc, is separated from Pelelieu, the southern member of the main group, by a saddle 6 miles wide and over 300 fathoms deep. In the center of the saddle there is a small bank, displaced slightly eastward, that reaches 8 fathoms.

Angaur is crescent-shaped, roughly 1½ by 3 miles. On the northwest tip there is a wide elevated reef, possibly a rim remnant, that is over 200 feet high. The remainder of the island is relatively level except for the low points on the north and east sides where the uneven surface of old reef rock lies. Excluding the emerged reef and a small pond in the northern part, the entire island lies within a few feet of sea level. Phosphate workings are located on the western and eastern sides of the island.

A well-developed fringing reef on the west side reaches a maximum width of half a mile off the southwest point (Fig. 3). On the south side the reef is narrow, and on the east and north sides it is largely absent and coral beaches lie between the low reef-rock headlands.

As shown by the isobaths, the underwater gradient is abnormally low off the southern half of the island where the 50-fathom line is as much as three-fourths of a mile off shore. Beyond this, submarine gradients are comparable to those found off the northwest and northeast points or off normal reefs in the tropics. Although seaward soundings to the north are inadequate along the main section of the arc for accurate evaluation of near-reef gradients, these are apparently normal except off Velasco Reef and Kayangal, a faroe, where there is some suggestion of a narrow bench.

FAIS ISLAND

Fais Island (9° 46′ N. Lat., 140° 31′ E. Long.) lies about 400 miles southwest of Guam and 50 miles east of Ulithi. Although Fais lies between Nero Deep and the Yap trough, the island is probably distant enough to be only indirectly affected by the diastrophic forces involved. Like Angaur Island, Fais lies in the northeast trades and north equatorial current during the greater part of the year and in the doldrums and counter equatorial current during the summer. The minimum surface water temperature is approximately the same as at Angaur.

Fais is approximately three-fourths mile wide and 1½ miles long with the major axis trending northeast-southwest. The island is a remarkably level plateau that lies approximately 100 feet above sea level. Because there are no rim remnants, it cannot be determined whether the island represents an elevated atoll or lagoonless coral island. Fais is surrounded by high cliffs that break abruptly from the upland on all sides. On the east and west ends of the island the cliffs are unprotected by reefs or beaches and wave erosion is particularly effective. Phosphate mining has been confined largely to the central portion.

On the north and south sides of the island narrow beaches lie beneath the cliffs

(Fig. 4). These are faced seaward by a fringing reef up to 1500 feet wide, the normal width for atolls of the Caroline and Marshall islands. Submarine gradients off the reefs as well as the cliffed headlands are abnormally low. On the east, the windward,

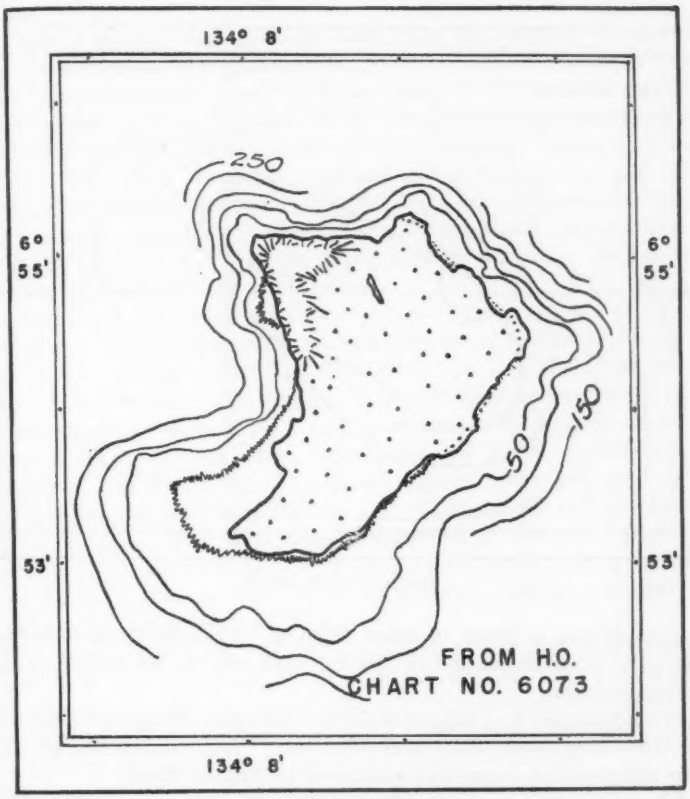

FIGURE 3.—*Angaur Island*

side the 50-fathom isobath lies nearly three-fourths of a mile off-shore and individual soundings of 23 fathoms are as much as half a mile out; one sounding of 2 fathoms is over one-fourth mile off-shore. On the north, west, and south sides the 50-fathom isobath is up to three eighths of a mile off-shore, which would barely provide space for rim reef growth and for resumption of the normal submarine gradient if the rim is assumed to have been removed by erosion. Beyond the 50-fathom isobath submarine gradients, although lower than off atolls in these waters, increase appreciably.

NAURU AND OCEAN ISLANDS

Nauru was administrated by Germany from the beginning of the century until seized by Australian forces early in World War 1. Subsequently the island was

placed under British mandate. The British claimed and integrated Ocean into the Empire in 1901, and used it thereafter as the seat of government for the Gilbert Islands. Phosphate was mined until the islands were occupied by the Japanese in 1942. Although Ocean was not fortified, Nauru, with the completion of two air

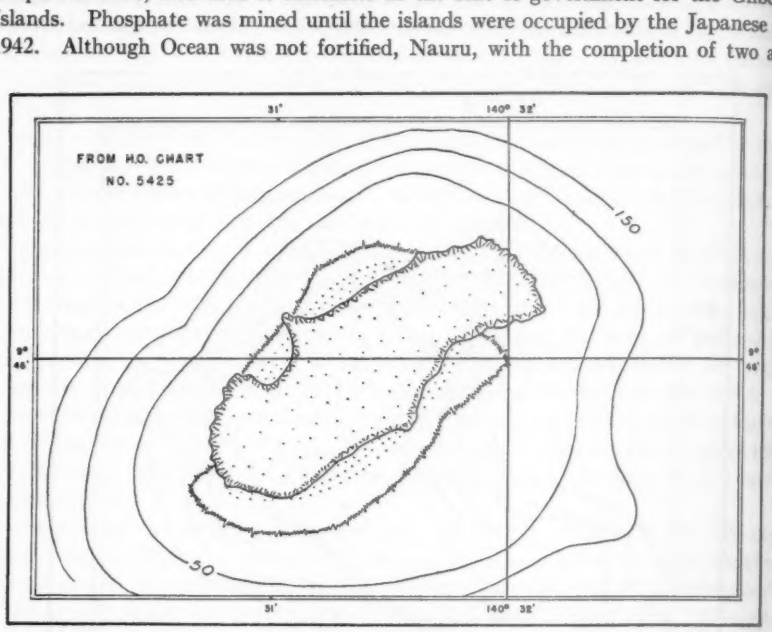

FIGURE 4.—*Fais Island*

strips, soon became a threat to Allied shipping. The islands were isolated and interdicted by American sea and air power in 1944 and were returned to the British after the capitulation.

Nauru was described by a number of German geologists during their tenure (Davis, 1928, p. 419); later Owen (1923) discussed Ocean. Both are interestingly depicted from the historical and commercial viewpoints by Robson (1944).

The islands are 160 miles apart, immediately south of the equator and about 500 miles west of the Gilberts. Nauru and Ocean are the only islands in a vast expanse of the Pacific west of the Gilberts and south of the Marshalls. Although the region has been inadequately charted bathymetrically, the available data show no evidence of instability. Both are influenced mostly by the southeast trades and south equatorial current, although in the winter (northern hemisphere) they come under the influence of the doldrums and counter equatorial current.

Nauru Island (0° 31′ S. Lat., 166° 56′ E. Long.) is kidney-shaped with axes approximately 2 and 3½ miles. It is circumscribed by a narrow fringing reef that varies in width from 300 feet off the southwest to 1000 feet off the northwest. At high-tide level, a sandy beach about 100 feet wide separates the reef from a near sea-level

flat that encircles the island. This peripheral flat varies in width from 1500 feet on the southwest, the side of the phosphate processing, to 300 feet on the northeast; on the north and northeast several ponds lie on the inner part of the flat. A steep declivity at the inner margin separates the flat from the main, and upland, portion of the island.

The upland area of Nauru averages more than 100 feet, and is unique among elevated atolls because of the amount of relief within what is apparently the former lagoon. Elevations range from 213 feet on the rim on the southwestern side to the sealevel of Buada Lagoon. The rim, which is contiguous to the lagoon and is found only along about one-fourth of the upland margin, averages 150 feet high and is up to 2500 feet wide. It has remnants of two shallow boat passes and an axial ridge that rises nearly 50 feet above the general rim level. Away from the Buada area the upland, which is of similar height and exhibits hummocky topography, grades imperceptibly into the rim. Most of the phosphate mining has been confined to the rim, although some workings have expanded to the upland.

This absence of rim around the greater portion of the island can be explained in several ways. First, it is possible that the hummocky surface has developed on lagoon deposits that had almost filled the lagoon to the level of the rim, that Buada Lagoon is a small remnant, and that the rim around the greater portion of the island has been removed by wave action. Second, the same conditions may have obtained except that the lagoon was almost entirely filled by detrital inwash and organic accumulation, and that Buada Lagoon subsequently developed by solution, as undoubtedly much of the hummocky area did. Third, the rim may continue around the island, altered until it is no longer distinguishable from the lagoon deposits. Last, Nauru may represent an elevated lagoonless coral island rather than an elevated atoll and Buada Lagoon may have formed by solution. Obviously, the medial ridge and boat passes weaken this hypothesis.

Although Ocean Island has been considered part of the lagoon of an elevated atoll, Owen (1923, p. 13) concluded that the island was more probably a coral platform. It is impossible to clarify this question here, but the question is of relatively little consequence because a lagoonless coral island differs from an atoll only in that the lagoon has been filled or that a rim had no opportunity to develop.

Ocean, somewhat smaller than Nauru with the greatest diameter less than 2 miles, is nearly circular except for a shallow bight on the southeast side, and is surrounded by almost vertical cliffs less than 50 feet high except off the southern point where the descent is gradual. The small central upland, almost 300 feet above sea level, is surrounded by three concentric terraces separated by steep declivities.

Owen (1923, p. 3, 4) described the structure of the island as consisting of

> "a mass of dolomitized coral . . . shaped like a flat dome . . . capped by a deposit of phosphate, sometimes as much as 80 feet thick, but usually less than 50. . . . The topography of the coral basis of the island is almost entirely hidden by the capping of phosphate; but there is sufficient evidence available, particularly now that part of the phosphate has been removed, to form some idea of the shape of the underlying mass. This appears to consist of a number of roughly circular platforms bounded towards the sea by almost vertical cliffs, a section of the coral below the phosphate displaying a series of steps. These platforms have been much affected by subaerial erosion (prior to the deposition of the guano), and by the solutions leached from the guano . . ."

He further stated (p. 11–14) that without question the phosphate was derived from bird droppings; that the variation in phosphatic content was between 79 and 92 per cent tricalcium phosphate; and that the variation could be reliably correlated with the elevation, indicating that the older, and therefore richer, portion of the deposit was on the higher part of the island.

No adequate hydrographic survey exists. According to Owen (p. 3, 4), a platform of marine abrasion about 100 yards wide has been cut out of an older reef and is presently being extended inland. Beyond this fringing reef the few soundings indicate that the 100-fathom isobath lies about one-fourth mile off shore, scarcely room for a rim, if the island represents an elevated atoll.

PROBLEMS OF LOW-LEVEL ABRASION

A review of the physical aspects of these islands shows without doubt that Minami Daito Jima, Kita Daito Jima, Okino Daito Jima, and Marcus Island were subjected to low-level marine abrasion during the period of subnormal oceanic temperatures of Pleistocene time. Moreover, the fact that the south side of Angaur is bound by a narrow fringing reef with a shallow bank to seaward and that the east side of Fais is similarly related indicates that these islands were also subjected to low-level abrasion when coral growth was inhibited. While cliff formation around elevated coral islands in tropical waters may suggest the possibility of low-level abrasion without inhibited coral growth, it is doubtful that benches as large as these could have formed by this process in the time available.

Although lack of adequate hydrographic charts and evidence of shoal waters on aerial photographs make the existence of a subsea bench around Nauru conjectural, the peripheral flat separated from the upland by a steep slope suggests development on a wave-cut bench. Moreover, if the rim has been removed by erosion, that erosion probably occurred when the reef was unprotected. If, however, it is assumed that the rim encircles the island, the flat could represent a fringing reef.

Obviously any pre-Wisconsin coral formation within the zone of effective abrasion that had been elevated and survived the onslaught should manifest this attack by wave-cut cliffs and subsea benches extending to the abrasion level, unless recent coral growth or vertical movement have obscured them. Although the hydrographic surveys of most islands in the western Pacific (except those formerly held by the Japanese) are inadequate for an evaluation of subsea benches, cliffs are found on the east side of Buka and Bougainville islands, on the south side of Mussau, around a large part of Emirau, which also has a bank to the northeast, on the elevated atolls of Green, Pinepil, and Rennell, and on the elevated coral terrace islands of Saipan, Tenian, Aguijan, Rota, and Guam. Significantly all lie within the equatorial zone.

Since low-level marine abrasion was undoubtedly efficacious several times in some latitudes, the age of these emerged islands has important bearing on their genesis. Certainly they can not have formed in the 30,000 years alloted post-Wisconsin time; the evidence of low-level abrasion, ancient emerged fringing reefs, present lack of active coral growth, and the rim widths of Minami and Kita all attest greater age. Moreover, such thick phosphate deposits as found on Okino Daito, Nauru, and Ocean

cannot have formed in post-Wisconsin time, especially since bird life is by no means luxuriant on these islands now. In the writer's opinion, the best evidence supporting Davis' contention that coral reefs survived in the equatorial zone throughout Pleistocene is the phosphate deposits on the near-sea-level atolls and lagoonless coral islands of Baker, Howland, Phoenix, Sydney, Malden, Canton, Flint, Starbuck, Johnston, Jarvis, Caroline, Vostock, and Enderbury, none of which lies north of the equator in the western Pacific.

Although there is little doubt that coral faunas permit reef assignment to the various Tertiary periods, Umbgrove's (1946, p. 23–31) estimate that 70 per cent of recent corals were extant at the close of Pliocene indicates that assignment for the Pleistocene epochs may be impossible or unreliable. Although most Japanese studies have utilized microfossils, as far as known little attempt has been made to attain the refinement required for reference within the Pleistocene. Thus, age determinations leave considerable to be desired, but the significant fact determinable is that these emerged "phosphatic" reefs are pre-Wisconsin.

According to Owen (1923, p. 13), the fossil remains at Ocean are so altered as to be indeterminable except for a single tooth of *Carcharodon megalodon*. The range of this species precludes specific assignment but indicates an age greater than Pleistocene.

The micropaleontologic studies of cores from Kita Daito Jima provide an accurate record of the later history of two of the emerged islands. Hanzawa (Gardner, 1946, p. 39–42) found that the 431 meter core hole penetrated five zones. Zone 1 (2–103 m.) consisted of an indurated dolomitic limestone all younger than Burdigalian and equivalent to the Ryuku-Mariana-Palau raised coral reefs of Plio-Pleistocene age (Tayama, 1940; Gardner, 1946, p. 38, 39). Zone 2 (103–116 m.) was blue calcareous mud and porous limestone with evidence of a considerable hiatus between zones 1 and 2. Zone 3 (116–209 m.) was pure limestone that was assigned to Aquitanian. Zone 4 (209–394 m.) of unconsolidated calcareous sand, was also referred to Aquitanian. Zone 5 (394–431 m.), of fine-grained calcareous sand, was referred to Chattian. Thus, although the age of the rim is correlative with the elevated limestone of the Marianas, Carolines, and Ryukus, no assignment is made with respect to glacial stages. It is significant that no volcanic rock was encountered, that the two depositional hiatuses indicate periods of emergence or truncation, and that post-Oligocene subsidence has been relatively slight and interrupted by positive movements.

Age relationships for the remaining emerged islands can be evaluated at present only from geomorphic evidence, which only suggests a minimal age. Unfortunately, emerged reefs may be of considerable age in the tropics and the external appearance may be of little diagnostic significance. For example, the rims of the Loyalty Islands are well defined although paleontologic evidence assigns them to the Miocene.

From external evidence Minami and Kita appear youngest; neither has a fringing reef nor emerged fringing reef, yet the subsea bench requires formation of the rims no later than Sangamon time. It is noteworthy that the width of the rims is similar to the width at Nukuoro of the subsea inboard bench at 20 fathoms which is separated from the central lagoon at 50 fathoms by a steep declivity, a "two-story" atoll that probably formed by subsidence of a pre-Wisconsin atoll to the truncation level.

The absence of well-defined rims on the remaining islands limits comparisons of the upland areas. The sea-level and emerged fringing reefs, however, permit certain assumptions. The near sea-level reef at Marcus, shoal areas, and absence of present growth indicate that this reef formed in pre-Wisconsin time. Because the island appears considerably older than the reef, the upland must be as old as the second interglacial stage. If the same reasoning is used for Okino Daito, the slightly emerged reefs at two levels indicate that it is as old as the Aftonian interglacial stage.

Comparison of the islands in lower latitudes is difficult because of the general lack of rim remnants and because recent coral growth may have obscured pre-Wisconsin reefs. Tayama (Gardner, 1946, p. 38) assigned the elevated reefs of the Palau arc to Plio-Pleistocene, but since the elevated reef at Angaur is wider than most of the present sea-level barrier and atoll reefs in similar latitude, it must have formed in pre-Wisconsin time if Pleistocene truncation is accepted. Whether Fais is an emerged atoll or lagoonless coral island, the low level abrasion platform indicates that the upland is pre-Wisconsin.

If the peripheral belt at Nauru is assumed to result from wave action, pre-Wisconsin age is manadatory. The upland topography and thick phosphate deposits indicates considerable antiquity. Since the phosphate at Ocean is considered to have formed on a uniformly slowly rising mass (Owen, 1923) the concentric benches are conceivably correlative with the glacial stages.

Several hypothetical questions bear profoundly on problems of truncation. First, did the decrease in water temperature lag relatively behind the lowering of the oceans, and has the lag in larval colonization been appreciable? If so, reefs were probably in active growth at the present level on islands in the marginal belt that do not now support such growth.

Second, in attempting an analysis of zones of truncation based on correlations in various latitudes and longitudes, the question of wind, current, and temperature distribution arises. At present the heat equator lies throughout the year in the northern hemisphere except west of 170° E. Long; in February it lies about 5 degrees north of the equator from the 180th meridian eastward and in August it lies along the 10th parallel. The heat equator largely controls the position of the northeast and southeast trades and doldrums, and, concomitantly, the north and south equatorial currents and the counter equatorial current. It is doubtful, however, that these positions obtained during periods of glaciation. If the predominance of land in the northern hemisphere and the almost unbroken polar land screen cause the northward displacement of these zones, the cooling of the land and the debouchment of icebergs from the Cordilleran mass probably forced a southward displacement of several degrees. Some confirmation of this suggestion is found in the positions of marginal atolls: Wake (19° 18′ N. Lat., 166° 35′ E. Long.) is the northernmost atoll in the western Pacific except for the elevated atolls which do not support vigorous coral growth; in the south Pacific, atolls are found in the southern Tuamotus, south of the Tropic of Capricorn. Moreover, the distribution of low-lying coral islands with phosphate deposits suggests that a zone lying southward from the equator for more than 10 degrees in the relative longitude of the International Date Line may have been sufficiently warm for coral reefs to survive the Wisconsin, as Daly (1915)

supposed for parts of the East Indian area. Summer and winter temperature charts of the Pacific contain a large lobe of water of 28°C. extending eastward from the warmest part of the Pacific and covering this area. Note, however, that these atolls are vastly different from the members of the Marshall, Caroline, or Ellice groups. Like the southern Gilberts, the phosphatic atolls have abnormally wide windward reefs, some up to 3 miles, poorly developed leeward reefs, are very shallow, have many coral heads and some with cays considerably above sea level. In every respect they look like old atolls.

Third, what was the effect of the circulatory system on the distribution of coral? Davis (1928) thought that during periods of glaciation the Humboldt current and the temperature of the deep water off the coast of South America chilled the south equatorial current sufficiently to destroy the reefs and permit formation of cliffed shorelines on the Marquesas (10° S. Lat., 140° W. Long.), although he considered these latitudes within the equatorial zone farther west. In the north Pacific no appreciable variation in reef width can be detected in the latitude of low-level truncation from the eastern Marshalls to the western Carolines, a distance of 2500 nautical miles.

Fourth, since the banks off Angaur and Fais lie at the same level as the lagoons of normal atolls and barrier reefs in similar latitudes and apparently under similar ecologic conditions, why are these islands not surrounded by reefs located at the edges of the banks? Perhaps the drift of detritus across the narrow bank delayed larval colonization until the temperature of the water had risen somewhat above the critical point.

Fifth, since Minami Daito, Kita Daito, Okino Daito, and Marcus undoubtedly were unprotected by active coral growth during Wisconsin time, as were probably the other elevated islands, how have they survived? Why are they not small banks under 25 to 45 fathoms of water? If foundations tens of miles wide are to be truncated by marine planation, surely the relatively narrow flanks, rims, and lagoons will be reduced to the level of abrasion. To augment the problem, several of the islands apparently withstood the low-level abrasion of several glacial periods. Further, the paradox applies equally to all modern theories of coral-reef formation because all have embraced low-level abrasion in the marginal zone. Although several hypotheses can be invented to circumvent the enigma, all are largely unsatisfactory because they either abitrarily require unwarranted revisions in geologic thought or observation, or possess only limited application.

If the geomorphic evidence used in dating the visible portions of the islands is fallacious and if the temperature decline lagged far behind the withdrawal of water, it is possible that the interval of effective Wisconsin wave erosion was not sufficient to permit removal of the flanks exposed by eustatic lowering. Obviously, the wider benches off Anguar and Fais in lower latitudes than the Jimas detract from this hypothesis unless appeal is made to special conditions.

This apparent inefficacy of wave action may be reconciled along a similar vein if these elevated islands are considered to be late and if the estimates of the lengths of early glacial periods are in error. While varves date rather accurately the interval from the culmination of the Wisconsin advance, the duration of other periods have

been estimated largely by the degree of weathering of various till sheets and their areal extent. Thus, if it could be shown that the earlier periods of glaciation were considerably longer, it could be assumed that the larger islands were truncated during those periods and that Wisconsin time was sufficient to permit removal of pre-existing atoll rims but insufficient to allow removal of the exposed flanks of the elevated atolls. Since these flanks may be considerably older than the rims and much more resistant, the suggestion may be of merit when applied to the younger islands.

Another hypothesis predicates that elevation or depression of the islands after formation of the rims and phosphates limited the interval of effective wave erosion. Although the available hydrographic charts are inadequate for evaluation of minor subsea benches or terraces, the known positive and negative movements of various Pacific islands coupled with the elimination of the difficult age factor lend appeal to this hypothesis.

As Stearns (1946, p. 245–262) recently emphasized, an integration of the subsidence and glacial control theories permitted the similarity of physical relations manifest by atolls and barrier reefs, besides eliminating the difficulties required in truncating any large mass of volcanic rock or in removing detritus in a relatively short time. Yet, this logical revision eliminated the means by which the survival of these small elevated islands was easily explained; that low-level abrasion was greatly retarded because the coral crowned freshly truncated basalt, as, for example, the main part of Iwo Jima. This explanation was strengthened by the narrow wave-cut benches at Kusaie, reported Miocene (Hanzawa, 1942), those of the Hawaiian Islands, and those of the Nanpo and Nasei Shotos; by the fact that islands such as Yap, reported pre-Miocene and Miocene (Hanzawa, 1942), were not truncated in spite of the advanced degree of topographic reduction and weathering; and by comparison of the narrow low-level benches off elevated coral terrace islands such as Rota, Tenian, etc. Moreover, Woollard and Ewing's (1939) refraction survey of Bermuda showed that an early Tertiary seamount had been truncated at the prescribed level. Yet, the age relations at Kita Daito and Ocean drastically limit this theory's applicability to these elevated islands.

CONCLUSIONS

It is evident that the low-level abrasion benches around emerged islands in the equatorial zone as well as the marginal zone afford excellent corroboration of the Glacial Control theory. Further, the wave-cut cliffs not only are the expectable accompaniment of low-level abrasion on islands unprotected by active coral growth, but also substantiate the observations of cliffed shorelines on reef-encircled volcanic islands in the Caroline group. Moreover, the cliffed shorelines of the several elevated coral-terrace islands that lie scattered throughout the equatorial zone likely result from wave action during a period when the Pleistocene climate inhibited coral growth. Since, however, volcanic rocks at Bikini are at least 2000 feet beneath the surface (Dobrin, Snavely, White, Beresford, and Perkins, 1946, p. 1189), the hypothetical deleterious effects of mud on coral growth during low-level abrasion are precluded for the majority of the islands in Oceania.

The decipherable characteristics of sea-level atolls and barrier reefs have been frequently relegated to a minor role in genetic considerations because little could be determined concerning their foundations, but any acceptable theory must logically account for the remarkable similarities of atoll and barrier-reef structures in the equatorial and marginal zones. Considering the accord of lagoon depths and the general levelness of lagoon floors regardless of reef length/lagoon area ratios, and the uniformity of reef widths on large or small atolls and about volcanic islands of manifestly different characteristics, the requirements of scientific probability demand postulating the operation of like processes throughout a like period under like physical conditions. Appeal to an equilibrium between rate of detrital inwash and subsidence throughout various periods under various conditions (Davis, 1928) or to deep marine planation on various types of rocks in various zones without eustatic lowering (Ladd and Hoffmeister, 1936; Hoffmeister and Ladd, 1944) cannot satisfy the frequency distribution shown by depth plots (Nugent, 1946, p. 777). The Glacial Control theory eminently fulfills these requirements and, since the controversial ramifications have either been demonstrated in error or reconciled, it seems that the genesis of most sea-level atolls in the Pacific involved (1) the formation of a coral cap on a seamount, followed by (2) low-level marine truncation during a period of eustatic lowering when the decrease in temperature inhibited coral growth, in turn followed by (3) formation of the present reefs when the water returned to the warming oceans.

Although the data of this paper have added to the assemblage that favors low-level marine abrasion in most latitudes, paradoxically they have apparently attested to the inefficacy of such wave action. How these pre-Wisconsin small elevated islands have survived in the marginal zone cannot now be unequivocally answered.

Two noteworthy facts are presented by consideration of the phosphates. First, because of the mode of origin, any elevated pre-Wisconsin elevated reef may have phosphate desposits of commercial value. Second, since the phosphates on relatively low-lying atolls and lagoonless coral islands were probably formed in pre-Wisconsin time, a zone of nontruncation in the central Pacific is nearly mandatory, unless appeal is made to elevation or submergence. Thus, the Pacific apparently has two distinct types of low-lying reefs, youthful post-Wisconsin reefs, and older, broader pre-Wisconsin reefs.

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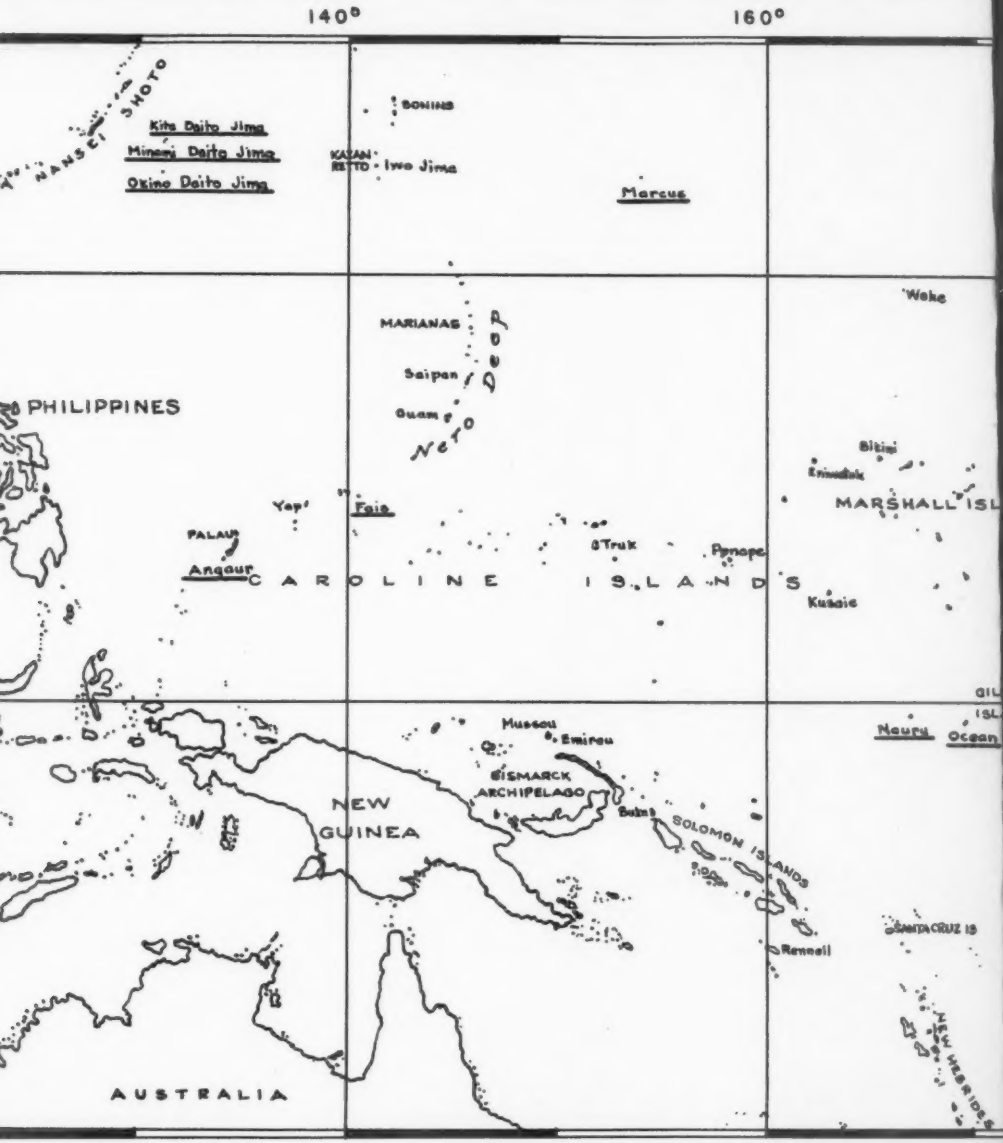
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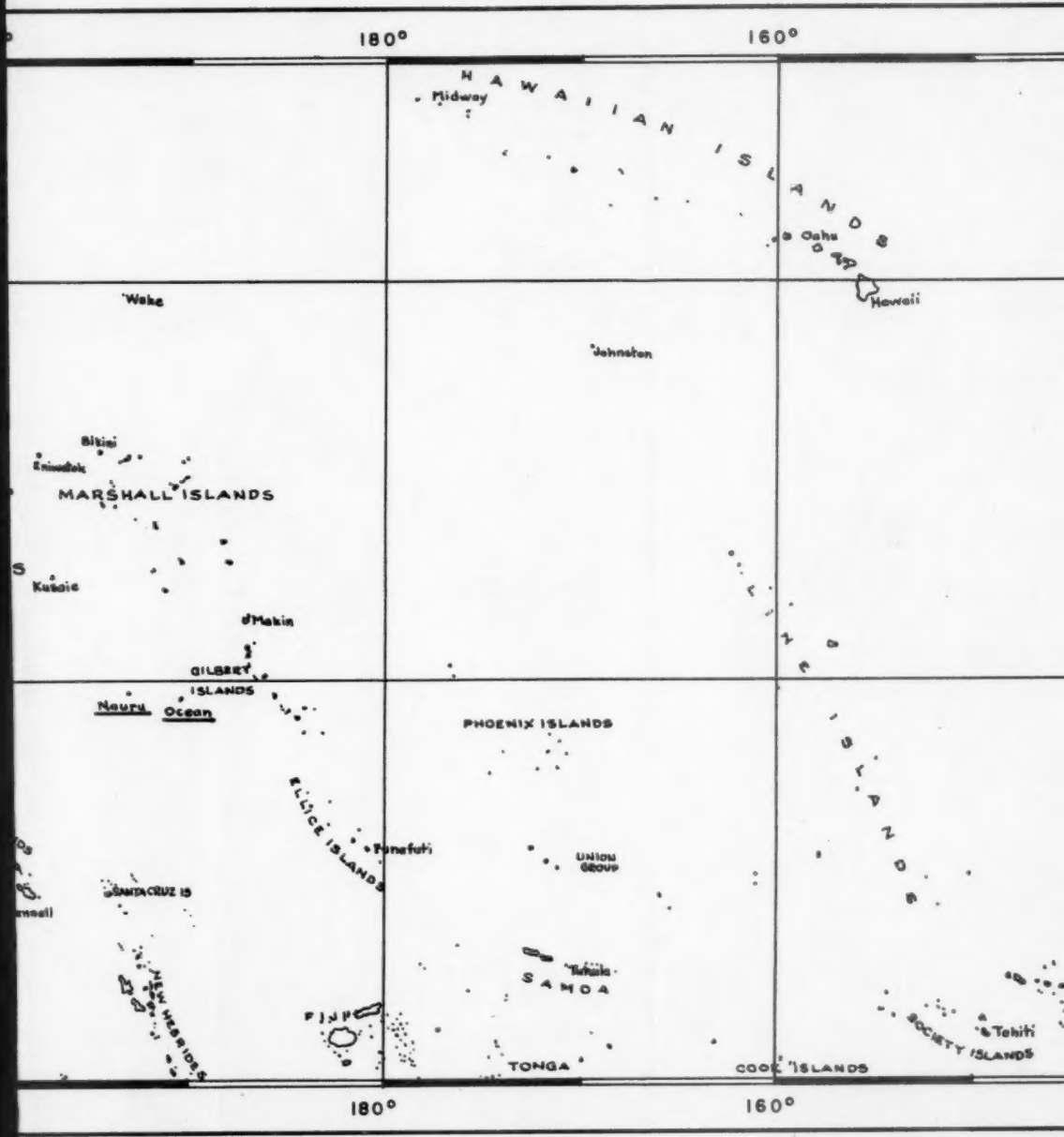

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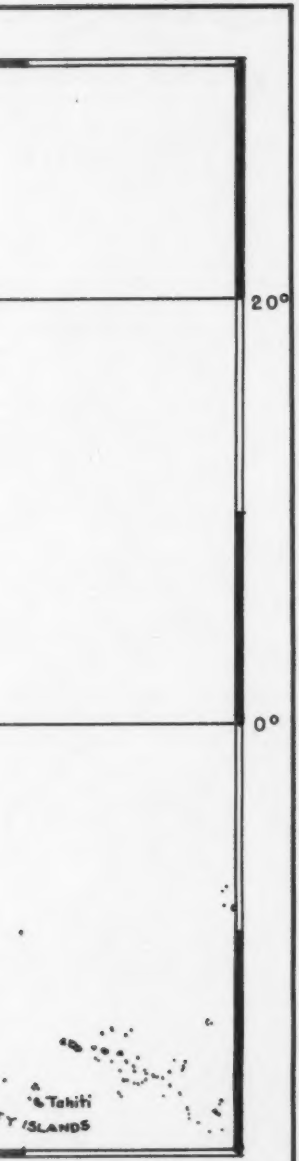
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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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GEOLOGY AND GROUND-WATER RESOURCES OF IWO JIMA

BY FRANK A. SWENSON

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ABSTRACT

Iwo Jima, in the western Pacific Ocean, consists of Motoyama, a broad volcanic cone, at the north, and Mt. Suribachi at the south, with an undulating isthmus between. Motoyama is largely light-gray-buff tuff. A thick andesitic lava flow under Suribachi, exposed in several places, is overlain by a thick deposit of cinder and scoria. The isthmus (called Tidorigahara by the Japanese) is underlain by more than 200 feet of loose black volcanic ash and fine cinder derived from Suribachi. Several small coral reefs are located about 340 and 110 feet above present sea level.

Iwo Jima first came into existence, probably early in Pleistocene time, with the building above sea level of the tuff cone of Motoyama. Quite late in the active life of Motoyama, volcanic activity on the southwestern flank resulted in the formation of Suribachi. This activity may have started with the welling up of the andesitic lava which underlies Suribachi. Following the major eruption of Suribachi, relative sea level changed, and the sea stood about 360 feet higher than at present. The broad cone of Motoyama was beveled; the relative sea level then dropped 240 feet,

with minor halts to about 120 feet above present level. As the island rose, Suribachi burst forth in its last stage of explosive activity. Wave erosion cut deeply into the andesite flow of Suribachi, and a prominent bench level was formed 120 feet above present sea level.

The Japanese on the island were often faced with serious water shortages. Americans drilled wells and obtained moderately large supplies of usable water. The temperature of the water ranges from 105° to 179° F., and the water is somewhat mineralized. The most favorable area for ground-water development is the isthmus.

INTRODUCTION

This paper is based on a month's field work between March 10 and April 10, 1945, and an additional week of study in June. Presence of enemy troops inconvenienced the work in the rougher northern part of the island. The investigation was made while the writer was a member of the Military Geology Unit of the U. S. Geological Survey and was serving with the military forces as a civilian consultant on water supply and engineering geology, assigned to the Pacific area by the Military Intelligence Division, Office of the Chief of Engineers, War Department. Mapping was done on a 1:10,000 scale military map with a 20-foot contour interval. The map was compiled from aerial photographs and did not show details of the rough terrain.

H. Tsuya (1936) spent 4 days studying the island in 1935, and the results of his investigation were published in English. Tsuya uses the modernized Japanese spellings, Io-sima and Suribati. However, it appears preferable in writing for American readers to use the older phonetic spellings. Tsuya gives several references to the geology of the island which were printed in Japanese, but these were not consulted by the present writer.

The writer wishes to acknowledge the help and co-operation of Col. D. A. Morris, USA, Island Engineer on Iwo Jima, and Lt. W. L. Morter of his staff. He is also indebted to Dr. Gordon A. Macdonald, U. S. Geological Survey, for petrographic determinations, and to Dr. C. K. Wentworth of the Honolulu Board of Water Supply for a critical reading of the manuscript.

GEOGRAPHY AND TOPOGRAPHY

Iwo Jima lies between 141° 17′ and 141° 21′ W. Long., and 24° 45′ and 24° 49′ N. Lat. in the western Pacific Ocean about 750 miles south-southeast of Tokyo and 840 miles east of Okinawa. It is 5.2 miles long in a northeast-southwest direction. From a maximum width of 2.6 miles on its northern bulge the island tapers to a width of less than 0.4 mile near the north base of Mt. Suribachi at its southern end. The island has an area of about 8 square miles. It is composed of a broad, low, volcanic cone, Motoyama, at the north, and steep Mt. Suribachi at the south, with a gently undulating isthmus of loose, black volcanic ash and fine cinder between. The highest point is Mt. Suribachi (556 feet). Motoyama rises to an altitude of about 360 feet. Steep wave-cut cliffs border the shore around both volcanoes, but fine sandy beaches border both sides of the isthmus. No streams exist, but gullies have formed rough bad-land topography around the flanks of the northern volcano.

Mt. Suribachi and the isthmus were barren of vegetation except for some pandanus

and sugar cane, planted in swales, and bunch grass and bean vines planted to stabilize the blowing fine cinder. The rougher northern part of the island, however, had fairly dense vegetation in most places. An oak woods, with some trees up to 2 feet in diameter, was growing on the upland near the east coast but much of this vegetation

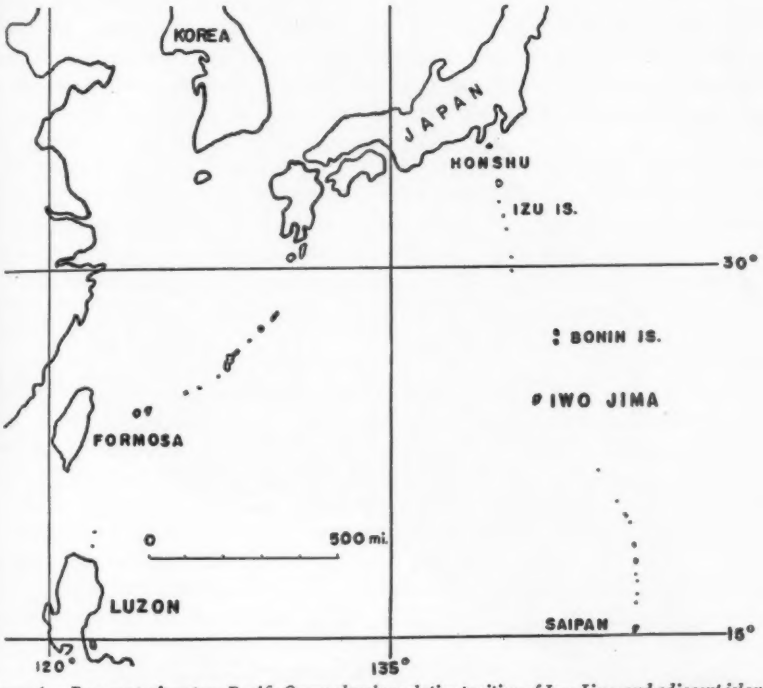

FIGURE 1.—*Base map of western Pacific Ocean showing relative position of Iwo Jima and adjacent islands*

was destroyed by combat and subsequent construction. Vegetable gardens seemed to flourish as did lemon grass, from which lemon oil is distilled, and Derris elliptica, from which the powerful insecticide rotenone is derived.

GENERAL CHARACTER OF THE ROCKS

Motoyama is composed of a light-gray-buff, thinly bedded tuff. Dips of beds around the flanks of the cone range from 9° to 14°, and strikes indicate that the crater lay near the center of the bulge of the island. There are no recognizable remnants of the crater. The tuff is very light in weight, has high porosity, but low permeability and thus is unfavorable for wells. It is soft and can be dug with power shovels. Since it breaks down readily under rolling it forms an excellent binder for roads in the loose ash and cinder area.

One rather thick bed of coarse agglomerate is exposed at sea level on the east coast.

The blocks of accessory ejecta in this agglomerate are mainly obsidian and dense, dark-gray andesite with some visible feldspar and augite phenocrysts. Blocks range up to several feet in diameter and make up more than 50 per cent of the bed. They

FIGURE 2.—*Geologic map of Iwo Jima showing locations of Japanese and American wells*

are enclosed in a solid matrix of dark-red to gray tuff (Pl. 1, fig. 1). The bed extends from below sea level to about 15 or 20 feet above.

Near the summit of Motoyama and across the northeastern part of the island the tuff is intruded by very irregular masses of intrusive rock (Fig. 2). These masses, which are as much as 500 feet thick, are dark and glassy rocks. The intrusive rock contains pockets of tuff, and typically forms miniature sill-like plates and tongues of twisty glassy lava. The lava appears to have intruded muddy tuff very close to the surface. The intrusion resembles intrusive pépérites in California (Macdonald,

1939) and the Auvergne region of France (Glangeaud, 1909). The intrusive rock is more resistant to erosion and in places forms ridges more than 50 feet high. Coarse boulder beaches have been developed where the intrusive rock has been subjected to wave erosion. During periods of heavy surf the noise made by the rolling and grinding of these boulder beaches is audible more than half a mile away. Part of one of these boulder beaches is pictured (Pl. 1, fig. 1).

The only other rock exposed on the northern bulge of the island is coral. Two small reefs, each about 10 feet across, were observed near the north-central part of the bulge. These reefs were solidly grown to a ridge of intrusive rock at an elevation of about 340 feet above sea level. Several fairly fresh-appearing pieces of finger coral were present on the reef.

Mt. Suribachi is composed of a thick flow of augite-hornblende trachyandesite with a thick cinder and scoria deposit overlying it. Blocks of pumice and scoria several feet across are fairly common on the crater rim. The pumice is a fine froth, and much of it floats on water. It is gray to red and very fresh looking.

The thick andesitic flow is exposed along much of the western side of the mountain, and small areas are exposed on steep slopes on the northeast and southeast sides at altitudes of 200 to 300 feet above sea level. On the west side wave erosion has eaten far back into the core of the mountain, and the crater rim is breached on this side. The andesite is medium to light gray and is fairly dense to porphyritic with phenocrysts of feldspar, olivine, and augite in an aphanitic groundmass. The rock is massive and has no uniform fracture systems. Contact with the overlying cinder and scoria is sharp without any pumiceous facies, which indicates weathering and erosion prior to the deposition of the ash and cinder. The base of the flow was not observed, although Tsuya (1936) reports a contact with an underlying agglomerate and tuff on the south side of Suribachi.

The undulating isthmus between Suribachi and Motoyama is fairly uniformly bedded black volcanic ash and fine cinder. The surface is soft, and one sinks into the soft ash and cinder several inches at each step. The material is poorly consolidated to a depth of 50 to 80 feet; it was necessary to drive well casing directly behind the drilling bits. The material is quite uniform in size, averaging about an eighth of an inch in diameter, but in a wave-cut cliff north of Mt. Suribachi coarser material may be observed (Pl. 1, fig. 2). A thin iron-cemented crust has formed over the face of the cliff.

Tsuya (1936) from a petrographic study believed the cinder and ash of the isthmus was derived from the residual larger fragments of the Motoyama tuff. This appears irreconcilable with the field observations that: (1) In many places the bedding of the ash and cinder deposit dips away from Suribachi, (2) the material in the isthmus is fresh and unaltered, unlike the weathered tuff of Motoyama but similar to the thick fresh cinder deposits on Suribachi, and (3) wells drilled near the north end of the isthmus passed through fresh ash and cinder to a sharp contact with weathered tuff similar to exposed Motoyama tuff. Two wells drilled 300 feet apart found a difference of altitude in this contact of more than 50 feet indicating considerable relief had been developed on Motoyama before the ash and cinder of the isthmus were deposited.

Along the beaches waves and long-shore currents constantly shift the loose cinder.

Several Japanese ships sunk along the east coast have blocked movement of the material and have been surrounded by wave-built bars. In general the surf is greater on the east coast, but even on the west coast ships, used for the development of a small boat harbor, have been broken up. Apparently the currents eroded the bottom from under both ends of the ships as the first sign of damage to the ships was the breaking of the back near the middle. Considering the quantity of cinder carried by the currents this harbor would probably not have long remained with usable depths.

EMERGED SHORE LINES

Several prominent emerged shore lines may be recognized. Motoyama has been bevelled by wave erosion. No sign of the crater remains, and a projection of the observed dips of the bedded tuff indicates that the volcano was once considerably higher than at present. In the bevelling the more resistant intrusive rocks were left as ridges, in places more than 50 feet above the surrounding plain. Suribachi was also attacked by the waves while the sea stood at this level, but much of the evidence was obliterated by the later explosive activity. Further evidence of this high stand of the sea is the presence of the two small coral reefs on the intrusive rock at an altitude of about 340 feet above present sea level.

The next most prominent bench is about 120 feet above sea level. This bench level is best developed along the northeastern shore of the island, where it is more than 500 feet wide. Thick deposits of coarse cobbles are found where the Motoyama intrusives are present. Many sea stacks and other shore features can be seen along the landward edge of this bench. Remnants of this bench level are also found near the southern end of the island around the flanks of Mt. Suribachi. When the sea stood at this level wave erosion cut back into the lava flow underlying Suribachi, and great deposits of cobbles were formed (Pl. 2, fig. 1). A large rock crusher set up at the north base of Mt. Suribachi utilized this source of hard rock for black-top surfacing of air fields and roads. Small fragments of marine limestone were observed on some of the larger boulders at an altitude of about 110 feet above sea level.

Broad flats with sea stacks, several having sea caves through them to form natural bridges (Figure 2 of Plate 2 shows such a stack with two visible caves), and rounded boulder deposits near dikes or other sources of hard rock suggest other emerged shore lines. Altitude of minor emerged shore lines could not be determined accurately.

GEOLOGIC HISTORY

It is impossible to determine exactly when Iwo Jima originated. The islands of the Volcano group are related genetically to the Recent volcanoes of the Tokyo area and the Izu Islands, while the parallel chain of islands making up the Bonin and Marianas groups originated as volcanoes in Tertiary time. The absence of the most recently elevated shore lines at 5 and 25 feet, described as eustatic by Sterns (1941), would indicate that age correlations cannot be made with other islands having raised shore lines at approximately the same levels.

Iwo Jima first appeared as an island when the accumulation of material ejected from Motoyama was raised above sea level. This may have been the result of

FIGURE 1. AGGLOMERATE BED EXPOSED AT SEA LEVEL
East coast of northern Iwo Jima. Cobble beach in lower foreground.

FIGURE 2. BEDDED CINDER DEPOSITS EXPOSED IN RAISED SEA CLIFF
North of Mt. Suribachi

AGGLOMERATE AND BEDDED DEPOSITS

FIGURE 3. STEAM-EXPLOSION PIT
West-central Iwo Jima.

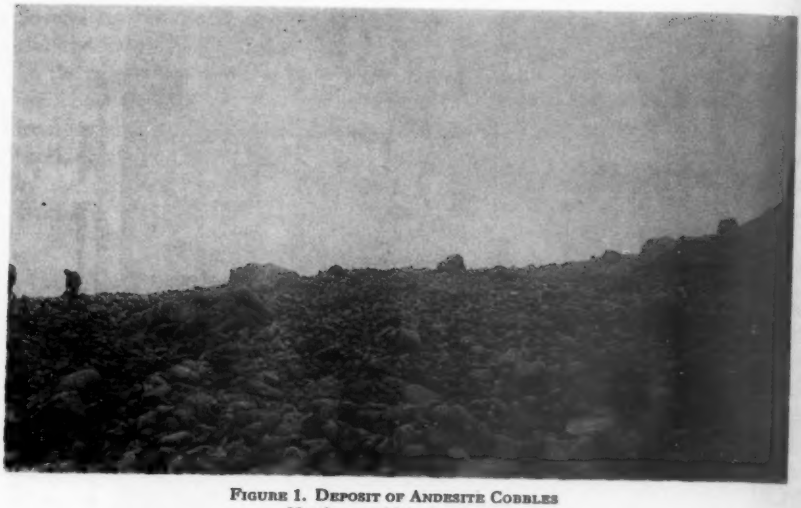

FIGURE 1. DEPOSIT OF ANDESITE COBBLES
Northwest of Mt. Suribachi

FIGURE 2. RAISED SEA STACK WITH TWO NATURAL BRIDGES
Formed by wave erosion, northern Iwo Jima.

crustal movement raising the sea floor on which the accumulated material rests, or it may have resulted when the rate of deposition exceeded the rate of destruction by the waves. Although Tsuya (1936, p. 458–459) suggests that the tuff may be a submarine deposit, the writer doubts that the light tuff could have maintained an underwater angle of repose as high as 15° at a relatively shallow depth in an area with such strong currents. Motoyama appears to have been an explosive type of volcano, as no flows were observed. The dikes which intrude its northeastern flank may have issued at the surface as flows, but, if so, waves have removed the evidence.

Probably quite late in the active life of Motoyama volcanic activity broke out about 3 miles away on its southwestern flank and built Mt. Suribachi. Little is known of the early history of Suribachi except that a mass of lava welled up at the site of the present mountain, and an explosive stage of activity followed. The agglomerate bed reported by Tsuya (1936, p. 460) may be a part of the agglomerate bed underlying Motoyama as he suggests. During the explosive stage there was eruption of the more than 200 feet of black volcanic cinder and ash found between Suribachi and Motoyama.

Following the major activity of Suribachi, and the active life of Motoyama, relative sea level changed. The broad cone of Motoyama was beveled by the sea. The poorly consolidated tuff was easily eroded by wave action and therefore only a relatively short period of submergence would be required. The lava flow under Suribachi was also eroded. As the island rose again the loose cinder deposit, derived from Suribachi, was reworked by the sea, and much of the present surface configuration of the isthmus came into being. The isthmus was somewhat protected from wave erosion by the solid masses of the two volcanoes, and this accounts for its wedge shape.

The relative level of the sea dropped, with several minor halts, until it was about 120 feet higher than at present. During this period, as the island was rising from the sea, Mt. Suribachi burst forth in its last stage of explosive activity. Much of the evidence of the emerged 360-foot shore line on Suribachi was buried. The sharp unconformable contact of the fresh cinder deposit and the weathered and eroded surface of the lava flow indicates erosion and weathering before deposition of the cinder.

This last explosive activity of Mt. Suribachi ended before or while the prominent 120-foot emerged shore line was forming. During this stand of the sea wave erosion cut far back into the core of Suribachi, and great deposits of andesitic cobbles were formed around the flanks of the mountain (Pl. 2, fig. 1). The presence of small fragments of coral on large boulders at an altitude of about 110 feet indicates that there has not been enough explosive activity since the sea stood at this level to bury these deposits at the north base of Suribachi. Cobble beaches were also formed at this time where the intrusive rocks on northeastern Motoyama were subjected to wave erosion. These raised boulder beaches have all the characteristics of those forming at the present time.

Since this well-developed 120-foot shore line was formed, relative sea level has gradually lowered. There were several minor pauses, but none was long enough for prominent shore lines to form. One of these pauses was at about 15 feet above present sea level. At this time the boulder deposits north of Suribachi were reworked, and a narrow bench was formed. Two of the Japanese wells were dug through a veneer of boulders on this bench.

The only later geologic events in the history of the island were the formation of two steam explosion pits. The larger pit, near the northern tip of the island, is about 600 feet long and 200 feet wide. Its walls are almost sheer, and the pit has a maximum depth of about 70 feet. A low rim of extremely fine-grained material surrounds this pit. Vegetation grows in the bottom and on the more gradual slopes of the pit walls. The other, much fresher-appearing pit, is about 0.3 mile from the west coast near the center of the island. This pit, circular in outline, is about 150 feet in diameter and almost 100 feet deep. The walls are sheer and show uniformly bedded material (Pl. 1, fig. 3). The pit was used as a dump. A crater rim, up to 5 feet high, of very fine-grained material surrounds the pit. No vegetation grows in the pit or on the crater rim. The fresh appearance of the crater suggests that the explosion may have occurred within the past few years. There seems to be no possibility that the crater was formed by anything but natural forces. Since no information could be obtained from the Japanese regarding the pit this could not be checked. Tsuya (1936, p. 471) states:

"There is no volcanic material that was ejected since the Suribatiyama (Suribachi) cone ejecta had been formed, nor is there any historic record of an eruption in the island. But volcanic activity is manifested in the island even at the present day by numerous solfataras. One of these solfataras on the northwestern side of Motoyama is said to have culminated a few years ago in ejecting a small volume of solid material. It is also said that detonations are often heard from the sea northeast of the island."

PRESENT STATE OF VOLCANISM

Many active fumaroles occur on the island. These are especially numerous in a belt extending northeasterly across the center of Motoyama, in the crater of Suribachi, and on the west beach area. Boiling mud is observed a few feet below the surface in the sulphur pit near the center of Motoyama. This appears to mark the location of the original crater of the volcano, where there seems to be the greatest concentration of heat on the island. The Japanese obtained sulphur commercially from the sublimate deposits made by these fumaroles. There is considerable heat at depth under the entire island, as indicated by temperatures ranging from 105° to 160°F. in wells drilled to sea level in the isthmus. One test hole drilled on the northwestern flank of Motoyama had to be abandoned at a depth of 242 feet because the temperature of the rock took the temper out of the bits. Steam issued from this hole under pressure great enough to lift a bucket off the top of the casing. There is a possibility of using holes of this type for heating of barracks, cooking, or even for power generation (Keller, 1946). The presence of the very fresh-appearing steam explosion pits indicates that such explosions may recur.

JAPANESE WATER SUPPLY FACILITIES

The Japanese were often faced with a serious shortage of water after the enlargement of their military installations on the island. Drinking water was obtained in a number of ways, several of which were quite unusual.

When the American landings were made there were 15 dug wells on the beach areas; they ranged from 14 to 40 feet in depth. Only 9 wells remained open; the others were blown up or caved in. Pertinent data on these wells are included in

TABLE 1.—*Japanese Dug Wells—Iwo Jima*

Number and location	Depth to water level	Depth	Chlorides (parts per million)	Temperature of water	Remarks
	feet	*feet*		°F.	
No. 1, NW. of Suribachi	14.5	17	2280	130	Cased with precast concrete rings; water clear and sparkling; pumped 30 gallons per minute. Diameter of well 4 feet.
No. 2, 200 feet N. of JW No. 1		13.5			Did not reach water table though at times water was available.
No. 3, 4500 feet N. of Suribachi				140	Mixed with sea water to cool it for shower use.
No. 4, 1200 feet from W. shore, N. end of beach area	25.6	27	280	106	Cased with precast concrete rings. *See* Table 3 for water analysis. Sample showed a trace of cyanide which disappeared on prolonged pumping. Japanese probably attempted to poison the well. Pumped 10 to 12 gallons per minute.
No. 5, 600 feet NE. of No. 4	22.9	25	6000	130	Cased with precast concrete rings; water has strong hydrogen sulphide odor; used for showers.
No. 6, at East Boat Basin		15	13,200	120	Well dug in tuff and probably had a very small capacity; was not cased; 4.5 feet in diameter. Well not used.
No. 7, 400 feet from shore at E. Boat Basin	40	43	2280	110	Square well cased with wooden planks. Water was not used.
No. 8, 200 feet SW. of No. 7	37.5	40	8400	120	Cased with precast concrete rings, not used.
No. 9, 3500 feet from N. end of East Beach	19.9	21	250		Well had a hexagonal wood casing; went dry in pump test. *See* Table 3 for water analysis. Well was not used. Diameter of well, 4 feet.

TABLE 2. —*American drilled wells—Iwo Jima*

Number	Altitude of curb	Depth of well	Altitude static water level	Drawdown pumping 30 gpm	Temperature of water	Production gallons per day	Remarks
	feet	*feet*	*feet*	*feet*	°*F.*		
US 1	193.85	195	8.7	0.3	128	40,000	In cinder entire depth. Analysis in Table 3.
US 2	199.2	200	15.0	0.9	142	40,000	In cinder entire depth. Pumping level dropped to 9.8 feet in 3 months. Chloride content increased to 2000 ppm. Analysis in Table 3.
US 3	185.46	190	7.5	0.9	110	40,000	In cinder entire depth. Analysis in Table 3.
US 4	180.3	183.5	7.1	Not tested	—	—	Well destroyed by explosives.
US 5	161	164	4.0	Not measured	124	40,000	Chloride content ±300 ppm. No complete analysis available.
US 6	146.5	155	10.2	10.	157	Low yield	Gray tuff entire depth. Water used for laundry. Analysis in Table 3.
US 7	282.	242	None	—	—	—	Hole abandoned as heat of rock prevented deeper drilling. Steam issued from hole under pressure.
US 8	152.2	161	11.2	Failed	179	Bailed dry	Drilled 150 feet into tuff. Analysis in Table 3.
US 9	204	211	10.	Not tested	—	—	Water under artesian pressure, 27,000 ppm total solids.
US 10	294	309	11.6	24	148	—	Lower 57 feet in tuff. Total chlorides 1200 ppm.
US 11	271	285	11.	0.1	140	—	Lower few feet in tuff. Total chlorides 2100 ppm.

TABLE 3.—*Chemical analysis of water in parts per million*

	JW#4	JW#9	US#1	US#2	US#3	US#6	US#8
Silica	95	146	120	136	120	135	228
Calcium	8.5	16	88	48	44	30	65
Magnesium	13	23	36	70	41	45	62
Sodium and Potassium	247	336	285	616	396	1260	2460
Ammonia	.5	2.5	0	0	0	.0	.0
Iron	2	12	15	2.5	35	1	18
Manganese	.05	1.6	.6	.8	.4	.0	.0
Aluminum	20	5.8	2.5	5.3	1.6	3.5	5.2
Bicarbonate	195	599	416	800	594	488	340
Sulfate	24	5.4	307	100	184	788	695
Chloride	280	250	253	690	375	1320	3450
Fluoride	.4	1	3.2	1.6	.9	1.6	1.6
Nitrate	7	0	0	.35	.33	—	—
Nitrite	.7	0	0	0	.01	—	—
Hydrogen sulfide	Tr.	11.7	—	—	—	—	—
Total solids	1020	1371	1497	2120	1537	3838	7272
Suspended solids	123	302	29	14	84	4	50
Dissolved solids	897	1069	1468	2106	1453	3834	7222
Total alkalinity	210	490	342	652	488	400	274
Total hardness	75	135	393	416	374	93	417
Carbonate hardness	75	135	342	416	374	—	—
Color	—	—	100	75	—	25	280
Ignition loss	143	227	196	186	184	172	624
pH value	7.5	7.2	6.5	6.5	6.6	7.6	6.8

Table 1. Pump tests were made, and 2 of the better wells were cleaned out and used for general purpose water; others were used for showers. The maximum yield of well No. 4 without appreciable rise in chloride content of the water was between 10 and 12 gallons per minute. The other well used supplied 30 gallons per minute safely, but the water had a total chloride content of 2280 parts per million so was not considered potable.

The Japanese distilled some sea water. An old Scotch marine boiler was set up as a make-shift still near the East Boat Basin. Fresh water was stored in a 10,000-gallon concrete tank under the building. The equipment was badly damaged, and the capacity of the plant could not be determined.

Water was also obtained by draining runoff from the southern airstrip and hard-stands into concrete and masonry reservoirs. The strip was paved with blocks of tuff, quarried on the southeast flank of Motoyama, and was quite impermeable. Eleven tanks, each with a capacity of about 28,000 gallons, were clustered near the east hard-stand of the field. Several others were under construction on the west side of the field and around the northern airstrip. Reservoirs were not roofed, but construction of roofs had been started. The tanks were placed so that when the first tank was filled the water would spill over into lower ones. Judging by the amount of runoff from the field during heavy rains of early April, a large quantity of water was obtained by this means.

The civilian population of Iwo Jima, which reportedly was moved off the island in June 1944, was mainly dependent on water stored in cisterns. Hundreds of cisterns had been carved out of the soft tuff of Motoyama. Most of these had artificially leveled and plastered catchments, but some stored rainfall which drained from the roofs. Most of these cisterns enlarged downward and were roofed with slabs of tuff. Capacity ranged from about 3000 to 15,000 gallons.

The finding of a badly damaged rotary drilling rig on the southern flank of Motoyama indicated the Japanese had started on a belated drilling program. The hole was not favorably located, and, although 147 feet deep, it was dry. No other drilled holes were found.

The most interesting and unusual Japanese water installations were those which condensed the steam from fumaroles. These installations ranged from simple ones consisting of a large funnel fastened over a fumarole with a pipe for cooling and leading the condensed steam into a bucket, to the large and rather complex installations over the main vents near the center of Motoyama. Small steam condensers, numerous throughout northern Iwo, provided many of the hold-out Japanese with water. Condensers were also present in the crater of Suribachi and in the fumarole area on the west beach. No information is available as to the quality of the water obtained. The fumes were corrosive to iron and caused the rapid breakdown of fill placed over fumaroles in building roads and air fields.

GENERAL WATER SUPPLY CONDITIONS

The loose, black volcanic cinder and ash of the isthmus is extremely permeable, and none of the rain falling on it reaches the sea as surface runoff. This great permeability was clearly demonstrated early in April when 3 days of very heavy rain was

climaxed by 4 inches of rain in 4 hours. In several places large quantities of water which fell on the relatively impermeable surface of the air fields ran off in torrents. Gullies up to 50 feet wide and 20 feet deep were cut in the edges of loose fill around the air fields, but, before the water forming these gullies had flowed much more than a quarter of a mile, it sank into the loose cinder.

This great permeability of the cinder, coupled with a heavy and fairly uniform rainfall, has resulted in the formation of a thick fresh-water lens underlying the isthmus. The highest known part of the lens is about 15 feet above mean sea level. Following the Ghyben-Herzberg principle of salt-water balance this would make the lens about 600 feet thick if there were no impermeable beds within this depth.

Motoyama is underlain by a fairly impermeable tuff; this fact plus the evidence of greater heat under this section of the island indicated that it is a less favorable area for ground-water development. The Japanese here made their one attempt to obtain water from drilled wells.

AMERICAN WATER SUPPLIES

During the early stages of combat to take Iwo Jima from the Japanese the American forces were supplied with water brought from other bases or distilled from sea water by ship-based distillation units. As soon as beach areas were cleared, distillation units were set up on shore. The supplies of water available by these means were limited, and additional supplies were badly needed.

After a rapid geologic reconnaissance a site was selected for the first well, and drilling began on March 21, 1945. The Japanese were still putting up a stubborn defense on the northern end of the island during the drilling of this well. The first five wells drilled were located in the most favorable part of the island, but as pumps for all of these successful wells were not available it appeared to be an opportune time for test drilling the less favorable northern bulge of the island. Wells 6 to 10 inclusive were not successful in obtaining usable supplies of drinking water, but they served to indicate that the conclusion was correct that all ground water would have to be produced by wells drilled in the isthmus.

Table 2 gives the more pertinent facts regarding the 11 wells drilled by the middle of June 1945. Locations of wells are shown on the geologic map (Fig. 2).

QUALITY OF WATER

Analyses of water from the wells show a considerable range in mineralization. Possibly the most unusual feature is the high concentrations of dissolved silica and iron in several of the wells. Analyses of waters from the wells in the cinder isthmus show them to be rather uniform but considerably different from the water from the wells drilled in the tuff of Motoyama. Water from the tuff is much more mineralized and contains much higher concentrations of sulphates and sodium and potassium.

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PETROGRAPHY OF IWO JIMA

BY GORDON A. MACDONALD

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ABSTRACT

The rocks of Iwo Jima are augite and augite-hornblende trachyandesites, distinctly more alkalic than the ordinary andesites of Japanese volcanoes or the average world andesite. They are described, and chemical analyses are listed. Fumarolic gases have altered some rocks to a mixture of opal and clay minerals and have cemented tuff with opal, calcite, zeolite, and iron oxides.

INTRODUCTION

The petrography of Iwo Jima (Sulfur Island) has been discussed by Tsuya (1936)[1]. The writer can add little to Tsuya's descriptions. It appears worth while, however, because of the widespread current interest in Iwo Jima, to summarize briefly the descriptions, making then more easily available to American geologists. Moreover, as the examinations of the rocks were made independently, without knowledge of Tsuya's paper, the results serve as a confirmation of Tsuya's work. Several of the chemical analyses in Tables 1 and 2 have hitherto been available only in a paper in the Japanese language (Iwasaki, 1937).

The writer has examined suites of specimens from Iwo Jima collected by C. K. Wentworth of the Honolulu Board of Water Supply, P. E. Schulz of the National

[1] Tsuya uses the modernized Japanese spellings Io-sima (for Iwo Jima) and Suribati (for Suribachi). However, it appears preferable in writing for American readers to use the older phonetic spellings.

Park Service, and F. A. Swenson of the U. S. Geological Survey, to whom thanks are extended for the privilege of studying the rocks. Special thanks are due Mr. Goichi Nakamoto, Engineer of the Honolulu Board of Water Supply, for a partial translation from the Japanese of the paper by Iwasaki (1937).

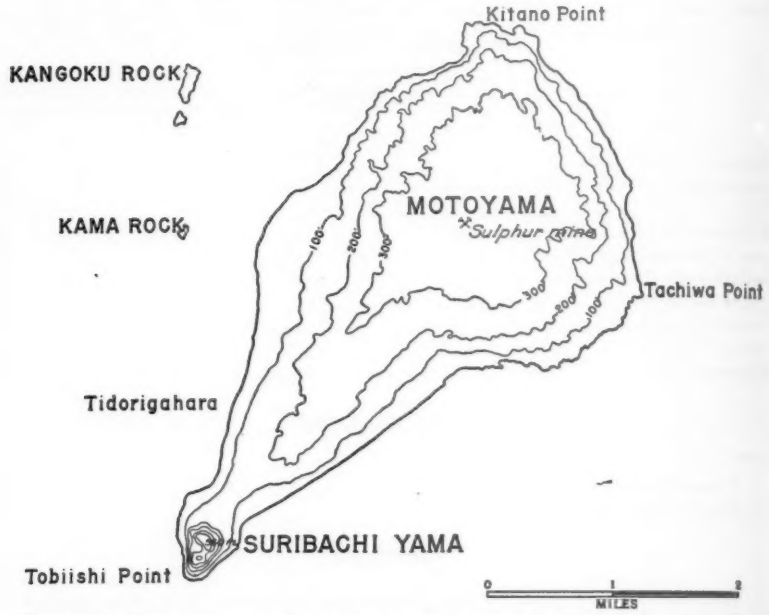

FIGURE 1.—*Topographic map of Iwo Jima, showing location of places mentioned in the text*

Iwo Jima and the neighboring islands Minami Iwo Jima (South Sulfur Island) and Kita Iwo Jima (North Sulfur Island) are volcanic islands lying slightly west of the nonvolcanic arc of the Bonin Islands, at the southern end of a belt of volcanic activity extending southward from the Idzu Peninsula and Fuji volcano on the major Japanese island of Honshu (Fig. 2).

The geology of Iwo Jima is discussed in the foregoing paper by Swenson (1948). Only the relationships of the major rock units will be summarized here. The relative position of the several topographic units is shown in Figure 1. Motoyama (Moto = cause or source, yama = mountain), which makes up the large northern part of the island, consists of the Motoyama tuff, intruded by the Motoyama intrusive bodies. The tuff dips outward in all directions from the summit of Motoyama. The southern end of the island consists of a bed of tuff, probably correlative with the Motoyama tuff, overlain by a lava flow which Tsuya termed the Suribachiyama (Suribatiyama) lava. The tuff and overlying lava flow dip gently southeastward. Overlying the lava flow is the later cinder cone of Suribachiyama (Suribachi = mortar or bowl for grinding, yama = mountain). Black cinder and ash, partly reworked into beach

sands and dune sands, cover the isthmus of Tidorigahara (Tidoriga = plover, hara = plain), north of Suribachiyama. The cinder and ash forming the surface of Tidorigahara was believed by Tsuya (1936) to have been derived largely by reworking of the Motoyama tuff but is thought by Swenson to have been formed by eruption of Suribachiyama.

TUFF

The Motoyama tuff is generally buff, more rarely grayish buff, in hand specimen. Some of the coarse bands are greenish. The upper phase is moderately well sorted, with the granularity of a fine sand; the lower phase is less uniform and coarser, containing many fragments of black glassy lava and buff pumice, and crystals of feldspar and augite, up to 8 mm long, in a fine matrix. Under the microscope the tuff is seen to consist largely of slightly altered pale-brown pumiceous glass shards, containing many crystals and fragments of crystals of andesine and augite, and a few of olivine, magnetite, and apatite. The glass has a refractive index of about 1.525 (1.521–1.526, according to Tsuya).

No specimens of the lower tuff bed in Suribachiyama were included in the collections studied by the writer. Tsuya (1936, p. 460, 478) states that it is similar to the lower phase of the Motoyama tuff, composed of small fragments of pumice and obsidian, and crystals of andesine, augite, and olivine.

MOTOYAMA INTRUSIVE BODIES

The rock of the Motoyama intrusive bodies ranges from a medium- or dark-gray lithoidal lava to a black obsidian. Moderately abundant phenocrysts of plagioclase reach lengths as great as 8 mm in some specimens, but more commonly 3–5 mm. A few phenocrysts of augite and rare phenocrysts of olivine reach lengths of 1–2 mm.

Under the microscope, the lithoidal facies is seen to consist of phenocrysts of medium to sodic andesine, augite, and a little olivine, and microphenocrysts of magnetite and apatite, in a holocrystalline groundmass. All types of phenocrysts except the apatite are commonly much rounded and embayed. Following resorption, a thin shell of more alkalic feldspar was deposited around the feldspar phenocrysts. The outer shell appears to have the same composition as the groundmass feldspar and was probably precipitated contemporaneously with the groundmass. Locally the olivine phenocrysts are altered around the edges and along fractures to limonite (?). The augite phenocrysts have an optic axial angle of about 55° (54.5° according to Tsuya). The olivine has a large negative optic angle (determined by Tsuya, with a universal stage, as 83°).

The groundmass of the holocrystalline facies consists of a mat of feldspar microlites, scattered through which lie grains of monoclinic pyroxene, magnetite, and apatite. The most abundant feldspar has a refractive index $\beta = 1.537$ ($\pm.003$). If it were pure soda-lime feldspar, this would indicate a mineral with the composition of albite-oligoclase; but the large proportion of normative orthoclase indicates that the groundmass feldspar probably contains considerable orthoclase. A few grains have a mean refractive index of about 1.528 and are probably anorthoclase. One specimen

contains a few small shreds of green biotite. Two specimens, from thin dikelets in the Motoyama tuff near the summit of Motoyama, contain veinlets of secondary calcite and calcite replacing feldspar and olivine phenocrysts. Rarely, the olivine is entirely replaced, leaving a pseudomorph of calcite.

The obsidian facies of the Motoyama intrusive bodies contains the same types of phenocrysts as the lithoidal facies. The groundmass ranges from partly to entirely glassy, and all gradations into the lithoidal type are present. Typically, it shows well-developed flow banding. In holohyaline varieties, discontinuous reddish-brown bands lie in more abundant nearly colorless glass with a refractive index of 1.524. Perlitic fractures are poorly developed, but tiny feathery and arborescent crystallites are abundant, especially along fractures in the nearly colorless glass, where their abundance results in deep-brown bands. Some hemihyaline specimens exhibit alternate bands of glass, heavily charged with finely granular magnetite, and bands consisting of a mixture of minute microlites of feldspar and pyroxene, also clouded with finely granular magnetite.

Chemical analyses of the Motoyama intrusive are given in Table 1. The rock is an augite trachyandesite.

LAVA OF SURIBACHIYAMA

The lava of the thick flow underlying the Suribachiyama cinder cone is medium to light gray and lithoidal. Tsuya (1936, p. 472) reports that it has a black obsidian crustal facies. It contains moderately abundant phenocrysts of feldspar up to 10 mm long, but mostly less than 5 mm, and a few phenocrysts of augite and olivine up to 2 mm. In most specimens the groundmass is holocrystalline.

The feldspar phenocrysts consist of a core of medium to sodic andesine, showing oscillatory zoning, enclosed in a thin shell of feldspar which appears to have the same composition as that of the groundmass. The feldspar phenocrysts were rounded and embayed before deposition of the outer shell. In a specimen collected by Wentworth on the western side of Suribachiyama, the feldspar of the shell of the phenocrysts penetrates the andesine core along irregular fractures, suggesting reaction of the andesine with residual fluids which penetrated the fractures. Locally, small amounts of groundmass pyroxene and magnetite have also been deposited along the fractures.

The augite and olivine phenocrysts, and microphenocrysts of magnetite, also are partly resorbed. Tsuya (1936, p. 473) reports that some of the augite phenocrysts are zoned, the optic angle decreasing from 55° in the center to 48° at the margin. Olivine has a large negative optic angle (84° according to Tsuya). Scattered microphenocrysts of apatite reach a length of 0.5 mm. One specimen from the northern base of Suribachiyama contains well-formed pseudomorphs of finely granular magnetite and pyroxene after phenocrysts of hornblende.

The groundmass consists of feldspar, monoclinic pyroxene, hornblende, magnetite, apatite, and rarely biotite. Tsuya (1936, p. 474–475) records the presence of two varieties of pyroxene, pale brown augite and green acmite; he found hornblende only in minute granules. In the specimens examined by the writer hornblende is abundant and forms subhedral prismatic grains up to 0.2 mm long. It is strongly pleo-

chroic with X = brownish green and Z = yellowish brown, Z ∧ c = about 21°, and moderate birefringence. The common pyroxene of the specimens in the collections studied by the writer is pale-brownish-green augite, with a large extinction angle.

FIGURE 2.—*Map showing position of Iwo Jima, Minami Iwo Jima, and Kita Iwo Jima, in relation to the Bonin Islands and the Japanese archipelago*

Small grains pleochroic from green to brownish green, with X essentially parallel to c, and high birefringence, are probably acmite.

A few minute shreds of biotite were found in two specimens. They are pleochroic from deep-greenish brown to greenish yellow, nearly uniaxial, and with strong dispersion; some grains show a strong ultra red on one side of the extinction position and ultra blue on the other. The feldspar of the groundmass is predominantly medium oligoclase ($\beta = 1.544$), but there is also present more alkalic feldspar with a mean re-

fractive index of about 1.529. Tsuya measured optic angles of 71° in the center of grains and 48° at the margin. The alkalic feldspar is probably anorthoclase.

Chemical analyses of the lava of Suribachiyama are given in Table 1. The rock is an augite-hornblende trachyandesite.

SURIBACHIYAMA CINDER CONE

The cinders comprising the cone of Suribachiyama range from medium gray to brown or red. Some contain moderately abundant phenocrysts of medium andesine, up to 5 mm long, and microphenocrysts of augite and magnetite, in a very fine-grained groundmass of medium oligoclase, monoclinic pyroxene, a little magnetite, and glass. Others have a glassy groundmass. Still others contain no macroscopically visible phenocrysts, but under the microscope microphenocrysts of andesine and augite are seen to lie in a glassy groundmass heavily charged with finely granular magnetite. Fragments of highly inflated buff to grayish-brown pumice consist of clear pale-brown glass (n = 1.523), containing a few microphenocrysts of feldspar, augite, and magnetite. No analysis of the cinder of Suribachiyama is available, but the rock is probably a trachyandesite like the other rocks of Iwo Jima.

SYENITE INCLUSIONS

Blocks of augite syenite in the Motoyama tuff and the sand on the isthmus are described by Tsuya (1936, p. 479). None were present in the collections studied by the writer. They are reported to consist of oligoclase, anorthoclase, iron-rich augite, olivine, magnetite, apatite, and interstitial glass. F. Homma is said by Tsuya to have reported aegirine-augite and cataphorite (?) in a similar block. An analysis of one of the blocks is given in Table 1.

FUMAROLIC ALTERATIONS

Solfataric gases issuing in the crater of Suribachiyama cinder cone have more or less extensively altered the rocks. Specimens collected by Schulz at the active solfataras at the eastern edge of the crater floor include more or less pumiceous cinder, and fine- to medium-grained ash, all partly or entirely altered. The rocks are bleached to light gray or white, and small grains of sulfur are deposited on the surface and in open spaces. Under the microscope the structure of the ash and cinder is seen to be perfectly preserved, but the rock has been altered to a mixture of opal and clay minerals, and in extreme examples to nearly pure opal (n = 1.448). The alteration closely resembles that in other solfataric areas (Anderson, 1936, p. 649–651; Macdonald, 1944a; Payne and Mau, 1946).

In the vicinity of solfataras in the Motoyama tuff, acid decomposition has in places altered the tuff to a fine sticky mud (Tsuya, 1936, p. 468). Elsewhere, as on the northwestern slope of Motoyama, the tuff along fissures from which solfataric gases formerly issued has been firmly cemented by deposition of veinlets and irregular masses of microscopic size of opal, calcite, zeolite, hematite, and limonite. In specimens collected by Wentworth, the cementation extends for an inch or two from the

TABLE 1.—*Chemical analyses of rocks of Iwo Jima*

ANALYSES

	1	2	3	4	5	6	7	8	9	10
SiO_2	58.45	58.56	58.59	58.83	58.91	59.30	59.60	60.32	60.55	60.82
Al_2O_3	18.05	18.13	16.54	18.09	17.71	16.61	16.81	16.09	17.29	16.63
Fe_2O_3	3.20	1.80	5.46	1.57	2.81	1.51	0.83	4.88	2.72	1.15
FeO	3.83	5.13	1.11	5.23	2.67	5.02	5.87	3.04	3.22	3.46
MgO	1.12	1.01	0.97	1.07	0.88	1.55	1.34	1.34	1.12	1.79
CaO	3.53	3.37	3.44	3.12	3.47	3.16	3.10	3.10	3.22	3.35
Na_2O	6.19	6.34	6.20	5.96	6.01	5.63	6.11	4.93	5.37	5.62
K_2O	3.81	3.61	3.69	3.68	3.94	4.41	4.17	3.90	4.36	4.21
H_2O+	0.27	0.43	2.42	0.54	0.34	} 0.95	0.25	} 0.65	0.53	} 1.84
H_2O-	—	—	—	—	0.30		0.10		0.21	
TiO_2	0.85	0.78	0.74	1.02	0.82	1.11	0.86	0.66	0.85	0.45
P_2O_5	0.42	0.46	0.37	0.51	0.49	0.44	0.50	0.56	0.28	0.22
MnO	0.10	0.20	0.20	0.30	0.16	0.21	0.26	0.25	0.19	0.39
$(Ce \cdot Y)_2O_3$	0.003	0.001	0.007	0.005	0.001	—	—	—	—	—
ZrO_2	0.009	0.010	0.005	0.013	0.005	—	—	—	—	—
BaO	0.127	0.130	0.129	0.133	0.142	—	—	—	—	—
S	0.043	0.054	0.527	0.060	1.313	—	—	—	—	—
Total	100.002	100.015	100.398	100.131	99.971	99.90	99.80	99.72	99.91	99.93

NORMS*

Q	—	—	2.64	0.30	1.86	—	—	9.66	4.50	1.98
Or	22.24	21.13	21.68	21.68	23.37	26.13	25.02	22.80	26.13	25.04
Ab	52.40	53.45	52.40	50.30	50.83	47.68	51.35	41.92	45.06	47.16
An	10.01	10.29	6.39	11.68	9.74	6.95	6.12	10.29	10.29	7.78
Di wo	1.97	1.16	3.36	—	1.63	2.44	2.32	0.58	1.51	3.36
Di en	0.90	0.30	2.40	—	0.90	0.90	0.70	0.40	0.70	1.50
Di fs	1.06	0.92	—	—	0.66	1.58	1.72	0.13	0.79	1.85
Hy en	1.10	0.50	—	2.70	1.30	3.00	0.60	3.00	2.10	3.00
Hy fs	1.32	1.45	—	7.13	0.79	5.02	1.58	0.53	1.85	3.56
Ol fo	0.56	1.19	—	—	—	—	1.47	—	—	—
Ol fa	0.61	3.57	—	—	—	—	4.59	—	—	—
Mt	4.64	2.55	2.09	2.32	4.17	2.08	1.16	7.19	3.94	1.74
Il	1.52	1.52	1.37	1.98	1.52	2.12	1.67	1.37	1.52	0.83
Hm	—	—	4.00	—	—	—	—	—	—	—
Ap	1.01	1.34	1.01	1.34	1.34	1.01	1.34	1.34	0.65	0.34
Plagioclase	Ab_{84}	Ab_{84}	Ab_{89}	Ab_{81}	Ab_{86}	Ab_{87}	Ab_{89}	Ab_{80}	Ab_{82}	Ab_{86}

* Recalculated.

1. Augite trachyandesite; Motoyama intrusive body, exposed in the fumarolic area. I. Iwasaki, analyst. Iwasaki (1937, p. 1272).

2. Augite trachyandesite; Motoyama intrusive body, crystalline phase; about 10 meters above sea level in a cliff on the beach approximately 1 km southeast of the salt works on the northeastern coast of Motoyama. I. Iwasaki, analyst. (Iwasaki, 1937, p. 1272).

3. Trachyandesite; lava of Suribachiyama, exposed on the northeastern slope of Suribachiyama. I. Iwasaki, analyst. (Iwasaki, 1937, p. 1272).

4. Augite trachyandesite; Motoyama intrusive body, hyaline phase; same locality as number 2. I. Iwasaki, analyst. (Iwasaki, 1937, p. 1272).

5. Augite-hornblende trachyandesite; lava of Suribachiyama. S. Tanaka, analyst. Tsuya (1936, p. 477). Minor elements determined by I. Iwasaki (1937, p. 1272).

6. Trachyandesite; exact locality unknown, Iwo Jima. K. Yokoyama, analyst. (Tsuya, 1936, p. 477).

7. Augite trachyandesite; Motoyama intrusive body, Iwo Jima. S. Tanaka, analyst. (Tsuya, 1936, p. 477).

8. Trachyandesite; exact locality unknown, Iwo Jima. Japan Imp. Geol. Surv., analyst. (Tsuya, 1936, p. 477).

9. Augite syenite; block in Motoyama tuff, Iwo Jima. Ushijima, analyst. (Tsuya, 1936, p. 477).

10. Trachyandesite pumice; 1914 eruption of Sin Iwo Jima (New Sulphur Island). Japan Imp. Geol. Surv., analyst. (Tsuya, 1936, p. 477).

TABLE 2.—*Average chemical composition of Iwo Jima rocks compared with those of other areas*

ANALYSES

	1	2	3	4	5	6
SiO_2	59.23	48.74	57.87	57.90	59.59	59.74
Al_2O_3	17.26	18.81	17.80	17.71	17.31	18.86
Fe_2O_3	2.75	4.67	3.07	3.15	3.33	1.94
FeO	3.90	7.14	5.31	4.75	3.13	3.75
MgO	1.16	4.52	2.63	3.09	2.75	0.90
CaO	3.28	12.00	6.80	6.76	5.80	3.00
Na_2O	5.86	2.30	3.52	3.00	3.58	7.33
K_2O	3.95	0.27	1.43	1.49	2.04	2.89
H_2O+	0.74	0.34	0.91	1.27	1.26	0.12
H_2O-		—				0.26
TiO_2	0.85	1.02	0.82	0.63	0.77	1.02
P_2O_5	0.45	0.04	0.27	0.24	0.26	0.26
MnO	0.21	0.33	0.20	0.20	0.18	0.13
$(Ce \cdot Y)_2O_3$	0.003	0.004	—	—	—	—
ZrO_2	0.008	0.001	—	—	—	—
BaO	0.132	0.018	—	—	—	—
S	0.399	0.006	—	—	—	—
Total	100.182	100.209	100.63	100.19	100.00	100.20

NORMS

Q	1.50	2.58	12.36	14.10	14.76	—
Or	23.35	1.67	8.34	8.90	11.68	17.24
Ab	49.78	19.39	29.34	25.15	30.39	58.16
An	9.17	40.03	28.91	30.58	25.30	10.01
Ne	—	—	—	—	—	1.99
Di wo	1.86	7.77	1.16	0.93	0.81	2.57
Di en	0.80	4.40	0.60	0.50	0.60	
Di fs	1.06	3.04	0.53	0.40	0.13	
Hy en	2.10	6.90	6.00	7.20	6.30	—
Hy fs	2.77	5.02	5.81	5.02	1.72	—
Ol fo	—	—	—	—	—	3.50
Ol fa	—	—	—	—	—	
Mt	4.18	6.73	4.41	4.64	4.87	2.78
Il	1.52	1.98	1.52	1.22	1.52	1.98
Ap	1.01	0.34	0.67	0.34	0.67	0.67
Plagioclase	Ab_{54}	Ab_{33}	Ab_{51}	Ab_{43}	Ab_{53}	Ab_{84}

1. Average of analyses 1 to 9 of Iwo Jima lavas in Table 1.

2. Basalt; Lava of Kita Iwo Jima (San Alessandro Island), collected on the northeastern side of the island. I. Iwasaki, analyst. (Iwasaki, 1937, p. 1272).

3. Average of 24 lavas from the Fuji region, Japan, with silica content between 55 and 60 per cent. (Iwasaki, 1937, p. 1273).

4. Average of 124 volcanic rocks of Japan, with silica content between 55 and 60 per cent. (Iwasaki, 1937, p. 1273).

5. Average world andesite. (Daly, 1933, p. 16).

6. Oligoclase andesite; Iao Valley, West Maui, Hawaiian Islands. M. G. Keyes, analyst. (Washington and Keyes, 1928, p. 203).

Daly, R. A. (1933) *Igneous rocks and depths of the earth*, 598 pp., New York.

Iwasaki, Iwaji (1937) *Geochemical investigations of volcanoes in Japan: X. Chemical compositions of the lavas of Iosima (Sulphur Island) and Kita-Iosima (San Alessandro Island), Volcano Islands Group* (in Japanese), Chem. Soc. Japan. Jour., vol. 58, p. 1269–1279.

fissure. The greater resistance to weathering of these cemented masses causes them to stand up in relief above the surrounding tuff. They closely resemble the "fossil fumaroles" in the deposits of *nuées ardentes* on the flanks of Mount Mazama (Williams, 1942, p. 86).

CHEMICAL ANALYSES

Table 1 shows the modern chemical analyses and norms of rocks of Iwo Jima, and also that of pumice from the submarine eruption which built up a short-lived new island 3 miles west of Minami Iwo Jima in 1914. Two incomplete older analyses have been omitted. They are listed by Washington (1917, p. 1038–1039).

The chemical composition of the rocks of Iwo Jima was compared by Tsuya (1936, p. 478) with that of the trachytes of Hawaii. It is even more like that of Hawaiian oligoclase andesites, an analysis of one of which is given in column 6 of Table 2, for comparison. Both Tsuya and Iwasaki (1937) point out that the Iwo Jima rocks are decidedly more alkaline and contain less normative quartz than the typical andesites of Japanese volcanoes. Table 2 gives the average composition of Iwo Jima lavas and the average compositions of lavas of comparable silica content from the Fuji region and Japan in general. The Iwo Jima lavas are also richer in alkalies and poorer in lime and magnesia than Daly's average world andesite (Table 2, column 5). In this connection it is of interest to note that Iwo Jima and the associated islands Kita Iwo Jima and Minami Iwo Jima lie on the inner (concave) side of the Bonin-Marianas arc (Fig. 2). The trachyandesite of the submarine eruption which took place 3 miles west of Minami Iwo Jima in 1914 (Table 1, column 10) closely resembles the rocks of Iwo Jima. However, the basalt of Kita Iwo Jima (column 2, Table 2) shows no apparent alkaline characteristics. The minor oxides in the Iwo Jima lavas are similar in abundance to those in other Japanese lavas, except that the average BaO content is appreciably higher than in the average lava of the O Shima (.020) and Asama (.038) areas or Kita Iwo Jima (Iwasaki, 1937, p. 1276), or in the average igneous rock (.055) of Clarke and Washington (1924). The proportion of sulfur is too variable to be significant.

The fact that the lavas of Iwo Jima are markedly alkaline whereas the basalt of Kita Iwo Jima is not may not be of any special significance. Even on a single volcano, such as Tutuila in Samoa or several of the Hawaiian Islands, the basalts may be subalkaline but the andesites and trachytes strongly alkaline (Macdonald, 1942; 1944a; 1946). The significance of the higher BaO content of the Iwo Jima lavas is not clear. In the relatively few alkaline andesites and trachytes of mid-Pacific volcanoes in which it has been determined, the percentage of BaO is about the same as that in the lavas of Kita Iwo Jima, O Shima, and Asama and is much lower than that in the rocks of Iwo Jima.

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OBSERVATIONS OF RELATIVE GRAVITY AT PARICUTIN VOLCANO

BY VIRGIL E. BARNES AND FREDERICK ROMBERG

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ABSTRACT

A set of observations of the relative gravitational force was made in the vicinity of and mostly north of Paricutin Volcano, State of Michoacan, Mexico. These data are given on a map, showing location and residual force for each observation, and contours of the force. No connection between the observed gravitational field and the volcano itself was found. A correlation between the observed force and the geology of the area is suggested.

PURPOSE

The primary purpose of the observations was to see whether the gravitational field showed any anomalies or unusual features which might be connected with the volcano. A secondary purpose was to establish stations where a change in the gravitational force due to future volcanic activity might be observed.

INTRODUCTION

This report concerns observations of the relative gravitational force in the vicinity of Paricutin Volcano, State of Michoacan, Mexico, May 6–24, 1945. The work was undertaken under the auspices of the National Research Council, with Dr. Richard E. Fuller, chairman of the U. S. Committee for the study of Paricutin Volcano, in charge. The expenses of the expedition were defrayed by a grant from the Geological Society of America. The force of gravity was observed at 74 representative stations and a map of the surface gravitational field near the volcano was drawn.

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GEOLOGY

Paricutin Volcano is a present day manifestation of an event that has happened countless times in the volcanic belt of Mexico. Volcanic cones of the same general magnitude abound in this region and much of the area surveyed is over thick piles of debris which includes an unknown proportion of lava. The materials poured forth from these smaller cones are basic in character and if compact would have a rather high density. However, these materials are extremely porous and the bulk density as indicated by the elevation force graph is about 1.8.

Paricutin Volcano is at the foot of a much older and larger volcano, known as Tancitaro, which is composed of andesitic rock. The regional gradient shown by the gravity map indicates that its bulk density is higher than that of the surrounding basic rocks.

PHYSICAL CONDITIONS

The surface near the volcano is completely covered with volcanic ash or new lava flows. The flows are impassable for horses or mules except where trails have been built over them; a man could cross them slowly if he were not encumbered by burdens such as a gravity meter. The volcanic ash, from 1 to 10 feet thick in the area surveyed, covers all trails and roads. The Uruapan-Los Reyes road has been relocated through Angahuan. Horses and mules can go almost anywhere on the ash where the slopes are not too steep, though this is difficult and slow in some places. The area north and east of the volcano is generally accessible except where it is covered by lava flows, but south and west of the cone the country is rugged and not readily penetrated except along certain valleys and ridges. Stations were obtained

in the latter area only at some cost in time. The ash covered all possible water sources except at Pancingo, so that staying out with a pack animal was generally not practicable.

FIELD METHODS

The observations were made with a LaCoste-Romberg gravity meter weighing 25 pounds. This instrument, and the automobile storage battery needed to keep its temperature constant, was carried by a mule. The stations along the Uruapan-Los Reyes road were occupied using an automobile.

A base for the gravitational observations was chosen just outside the storehouse door, and the meter was read there before and after every trip it made. Auxiliary bases were established so that the meter could be checked at some base or previously read station every so often. This is necessary because a gravity meter drifts with the tidal force and residual temperature differences. Traverses are usually made in the form of interlocking loops to facilitate making check readings; this was difficult for the observations near the volcano as there were few paths into the hilly country and the meter had to be brought back to the storehouse every night.

Observations were made on all available topographic markers and magnetic stations previously established in the area, and on 40 other stations chosen to supplement these. The new stations were chosen to cover areas where there were no established markers, to break long traverses with the meter, and to set stations where the effects of local terrain would be small. Such stations could not be permanently marked at the time, and no elevations were measured for them until much later, when some of the stakes had been lost. The permanent stations did not cover the area, and most of them were on the tops of high hills; this is bad because the terrain effects on peaks are large and hard to compute, and the long climb necessary to reach them increases the probable drift error. Ground motion was observed on all stations; its amplitude increased toward the volcano until accurate readings became impossible at a distance of about a kilometer from the center of the cone. It would have been interesting to observe the amplitudes, frequencies, and fluctuation of the ground motion at different distances from the volcano with an instrument adjusted as a seismograph rather than as a gravity meter.

COMPUTATIONS

METHODS

The observations were corrected in the standard manner for drift, calibration factor, latitude, and elevation. The drift corrections were made from daily drift curves plotted from the readings on bases. The corrected dial reading was then converted to milligals with the meter's calibration factor. The co-ordinates of the stations were compiled from all available data, principally the topographic map based on stereoplanigraph compilation which was received February 5, 1947. The readings were then corrected for latitude (Nettleton, p. 52, 1940) with a correction of 0.511 milligals per kilometer, from an assumed latitude of 19° and 30′. The combined elevation

and Bouguer correction was found with a force-elevation graph to be 0.232 milligals per meter, and the stations corrected to an elevation of 2000 meters. Terrain corrections were made on certain stations with a Hammer zone chart (Nettleton, p. 145, 1940). The resulting values for the force were then plotted on a map and contoured.

HORIZONTAL POSITIONS OF GRAVITY STATIONS

The position of the G and M series gravity stations as given by the Oficino de Geografia were plotted on the topographic sheets. Since many of the plotted points did not coincide with their known position, they were adjusted and the new coordinates used for the final gravity computations. The adjusted locations of these stations are reasonably certain since their positions were plotted on an aerial photograph in the field. When an aerial photograph, scale 1:20,000, taken in May 1945 was received, the stations were transferred to it.

ELEVATION OF GRAVITY STATIONS

All the elevations furnished by the Oficino de Geografia were checked against the U. S. Geological Survey topographic map of the Paricutin area, received by the authors February 5, 1947. The 20 stations for which the stakes were recovered and which check within the proper contour interval when adjusted for position follow: G1, G2, G8, G9, G10, G11, G12, G14, G21, G28, G29, G32, M1, M2, M3, M5, M6, M7, M10, and M12. Raul Chavez pointed out the approximate position of 14 stations whose stakes were missing, and these check within the proper contour interval when adjusted for position. They are G3, G4, G15, G16, G17, G18, G19, G26, G36, G37, M4, M11, M13, and M14.

The position of 6 stations (G5, G6, G7, G13, G27, and G38) where stakes were missing appear to have been misjudged; elevations for these are estimated from the U. S. Geological Survey map. Three stations, G24, G25, and G30 are outside the contoured area and their elevations can not be checked, but as G30 is near the contoured area its elevation is estimated.

Ten stations were not recovered by the Oficino de Geografia. Of these, 7 (G22, G23, G31, G33, G34, G35, and Steenland's magnetic station No. 4) are within the contoured area, and their elevations are estimated from the contours. Stations G39, G40, and G41 are out of the contoured area. By using a Brunton compass as a hand-level, G39 was estimated to be about the same level as Canijuata. G40 and G41 were compared to the top of the volcano, which they approach, but these elevations are purely guesses made almost 2 years after the occupation of the stations. The elevations of named stations are from the U. S. Geological Survey topographic map.

It seems probable, from checking by the topographic map, that all points in the contoured area are within 5 meters of being correct, and that most are within 1 meter of being correct. The group of stations in which the stakes were recovered appear to be correct within a few tenths of a meter.

GRAPH OF ELEVATIONS AGAINST OBSERVED FORCE

One way to find the combined elevation correction for a gravity prospect is to plot a graph of the observed force (milligals) against elevation. The values of the

force are corrected for drift and latitude but not, of course, for elevation. The points on the graph should tend to lie on a straight line, with higher values of force for lower elevations. The slope of this line gives the combined elevation correction in milligals per foot. Since the free air correction is practially constant, the Bouguer correction may be deduced from the combined correction, and a value for the surface density found (Nettleton, p. 55, 1940).

The elevation correction on a prospect as determined by the elevation-graph method is of course subject to qualification as the study of the prospect is refined. If the elevations of the observation points are correlated with location, geological position, or even roughness of topography, then the computed correction tends to reflect this correlation. For instance, if the prospect slopes generally in one direction, the graphical elevation correction will include the regional gradient in this direction, if there is one. This is not harmful unless it is the regional gradient which is being sought. Again, if the higher points are on a different outcrop from the lower ones, the graphical correction will include the anomaly caused by the density difference of the outcropping formations. Finally, if, say, the higher elevations occur in the regions of rougher topography, the terrain corrections will be larger with higher elevations and may cause the correction to be greater than it should be, and the deduced surface density less. This could be checked for a given prospect by computing terrain corrections for low and high stations falling on the line and finding a new slope and density from the line through the corrected points.

On the Paricutin prospect, the force-elevation graph shows the points lining up in a line whose slope is 0.232 $\pm$ .005 milligals per meter, and this value was used for the combined free-air and Bouguer elevation correction for the prospect. The highest and lowest points do not fall in line with the general trend. These points may be anomalous because of high terrain errors, uncertain elevations, or other causes. The value of 0.232 milligals per meter corresponds to a surface density of 1.8 $\pm$ 0.1.

TERRAIN CORRECTIONS

With the aid of the topographic map, terrain corrections were computed for 23 stations. These included all stations on the topographic map which might give a terrain correction of over a half milligal. The largest correction was 5 milligals, at Zinzungo, which was at the apex of a high cone. Seven stations had corrections greater than 1 milligal; these corrections are probably accurate within 20 per cent. Errors in terrain corrections are therefore probably less than a half milligal (except at Zinzungo, Equijuata, and Capatzin). Such errors are not important in the final map because they are in general smaller than errors due to elevation.

The terrain corrections were computed with a Hammer zone chart (Nettleton, p. 145, 1940), to a radius of about 1.5 km. The contribution of irregularities farther away than 1.5 km. is generally small, and does not change much from station to station; it is therefore not likely to cause anomalies. The terrain correction is always positive; this tends to lessen the errors due to neglecting terrain effects at a distance. Examination of the list of corrections shows of course that the stations with the greater corrections are generally in the rougher, higher country. However, the average correction even in the hills is less than 1 milligal; a survey in comparatively rough country would thus be accurate to plus or minus 0.2 milligal, if accurate eleva-

tions and good topographic data were available and the stations were judiciously located.

RESULTS

ACCURACY

1. Instrumental error

Comparing successive readings on the same bases after drift correction shows an average error of less than 0.05 milligal. Some of the isolated stations could not be properly checked, but this is of little consequence as the errors in the corrections are perhaps ten times as great as the instrumental errors.

2. Latitude

The effect of errors in latitude will in most cases be less than that of the instrumental error.

3. Elevations

The effect of inaccurate elevations is obvious, since an error of 4.3 meters in the elevations gives rise to an error of 1 milligal in the computed force. Plus or minus 1 milligal is thus a liberal estimate for the accuracy of the final map.

4. Terrain corrections

The probable errors due to roughness of terrain have been corrected to less than a half milligal on all stations covered by the topographic map.

MAP

The map shows the locations of the gravity stations, the value of the force for each, and proposed contours for the force. The contour interval is 1 milligal. Anomalous values for the force have been ignored in drawing the contours where the elevations were felt to be questionable (such as at G13, G31, G6, G7, G40, and G41). The discrepancy between such points as M7 and Jaratiro, and G4 and Hornitos, is probably due to motions of the ground when these stations were being observed.

CONCLUSIONS

1. A zone of seismic activity or ground unrest around the cone prevents observations with the gravity meter nearer than 1 km. to the center of the cone.

2. The gravity map shows a regional gradient rising to the southwest at about 1.5 mg. per kilometer.

3. (a) A broad gravity ridge extends northeastward from the volcano.

(b) A sharp anomaly is outlined in the area of the stations Tiripan, Zicuin, and Ticuiro.

(c) A difference of over 4 milligals is observed between G2 and G38, and a difference of 3 milligals between G3 and Casita Canijuata. These differences are unconfirmed by other stations and thus may be due to an error in elevation or observation. However, it is interesting that they are in a northwest-southeast line with the Zicuin anomaly, to form in general an increase in the regional gradient in the southwest part of the map.

4. The force-elevation graph shows the surface density to be 1.8, plus or minus 0.1, for a considerable depth.

CORRELATION OF GRAVITY AND GEOLOGICAL DATA

Dr. Howel Williams (letter of March 20, 1947) makes the following statement concerning the geological conditions as related to the gravity anomalies:

"The broad gravity ridge extending from near the volcano northeastward through Capatzin may be controlled by one or more of the following factors:

a. A buried ridge of Tancitaro andesites. In general the lavas of Tancitaro are thick, massive flows of pyroxene andesite, and their average density is probably much higher than that of the vesicular basalts that rest upon them. Moreover, the latter are undoubtedly interbedded with much basaltic ash, whereas, the Tancitaro flows are accompanied by only rare and thin interbeds of pyroclastic debris. Thus the general density of the Tancitaro rocks is presumably much higher than that of the vesicular basalts and pyroclastic interbeds.

b. There may be a buried ridge of the plutonic basement. We know that Paricutin has blown out a lot of quartz monzonite. On the other hand few fragments of the pre-Tancitaro Zumpimito volcanics have been recognized among the ejecta, and no pieces of Tancitaro lava have been observed. The possibility therefore arises that the quartz monzonite fragments may represent portions of a plutonic floor at fairly shallow depth.

c. Most of the olivine basalts and basaltic andesites composing the visible ridge running northeast through Capatzin are denser and less vesicular than the normal basaltic flows of the region. The cliffs adjacent to Capatzin consist of unusually thick and massive lava rather than the scoriaceous and blocky basalts of the surrounding region.

"The northeast trend of the gravity ridge is approximately parallel to the main fissure zone at Paricutin itself, and this in turn is parallel to the trend of several large volcanoes and smaller cinder cones in the region about Capacuaro and Paracho. Indeed this northeast trend, as determined by the alinement of cones, is the only well-defined one in the 600 square miles that my map covers.

"I have no explanation for the anomaly in the vicinity of Zicuin and Ticuiro. In that region the blanket of Paricutin ash covers all but a very few small outcrops. The same blanket conceals all evidence that might explain the steep gradients between Tiripan and Canijuata. I can only guess that the gradient steepens here because of the form of the buried flank of Tancitaro volcano."

RECOMMENDATIONS

The gravity survey of Paricutin did not result in any specific discoveries which might encourage further work. There is a possibility that the anomaly mentioned in conclusion (3) may be significant. If the stations are ever repeated, the differences that will be observed will be of doubtful significance, as their locations were not permanently marked.

If gravity surveys are made of the area in the future, it is strongly recommended that the elevations be found at the same time the observations are made. Stations should be located in flat places, away from cliffs or gullies, as the effect of rough terrain dies away rapidly with distance. For a complete map of the area, the country south of the volcano should be surveyed; this would have to be done from camps, with a pack train to carry water and supplies.

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The University of Texas, Austin, Texas; LaCoste and Romberg, Austin, Texas.
Manuscript Submitted to the Secretary of the Society, March 25, 1947.
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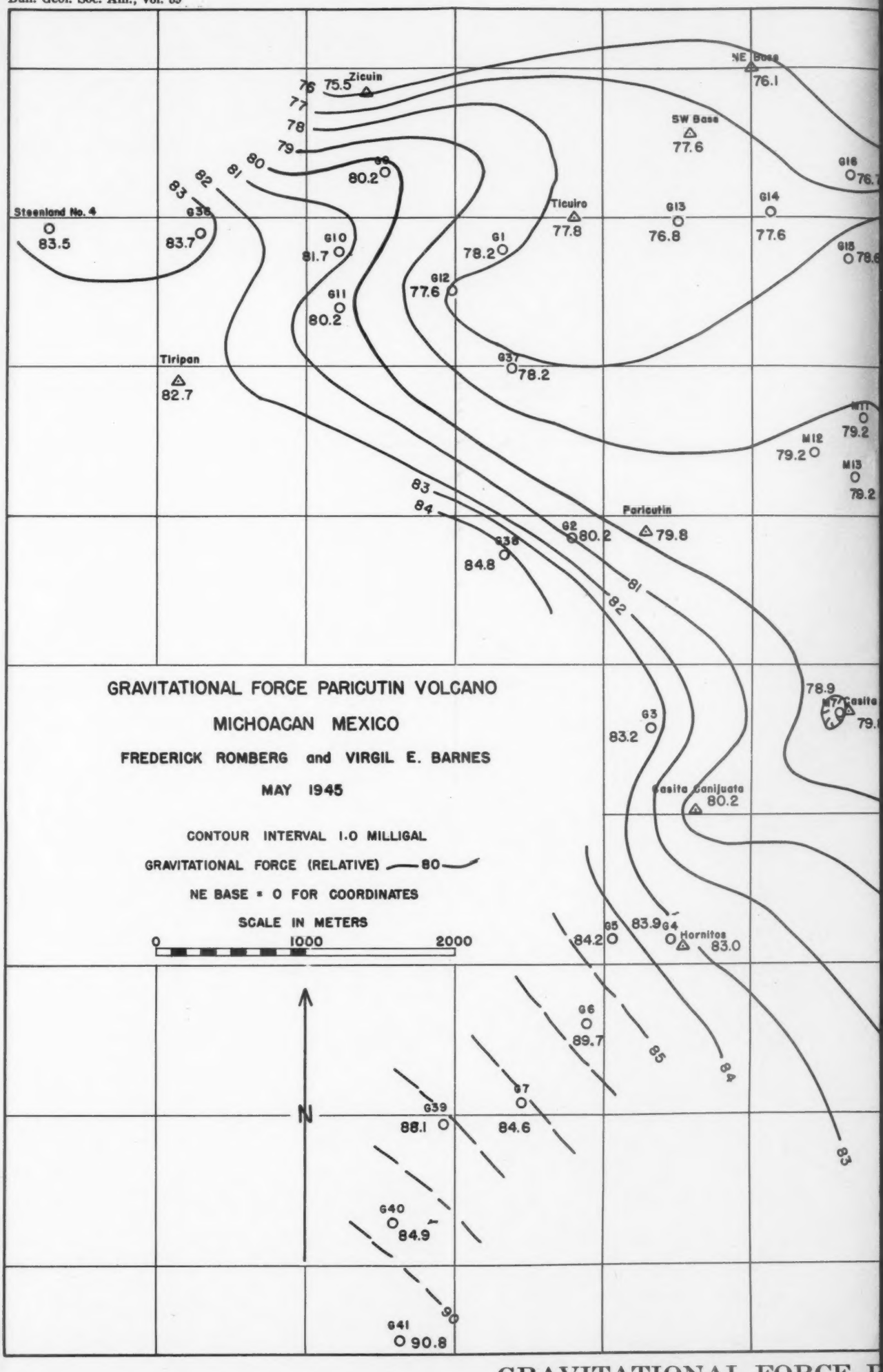

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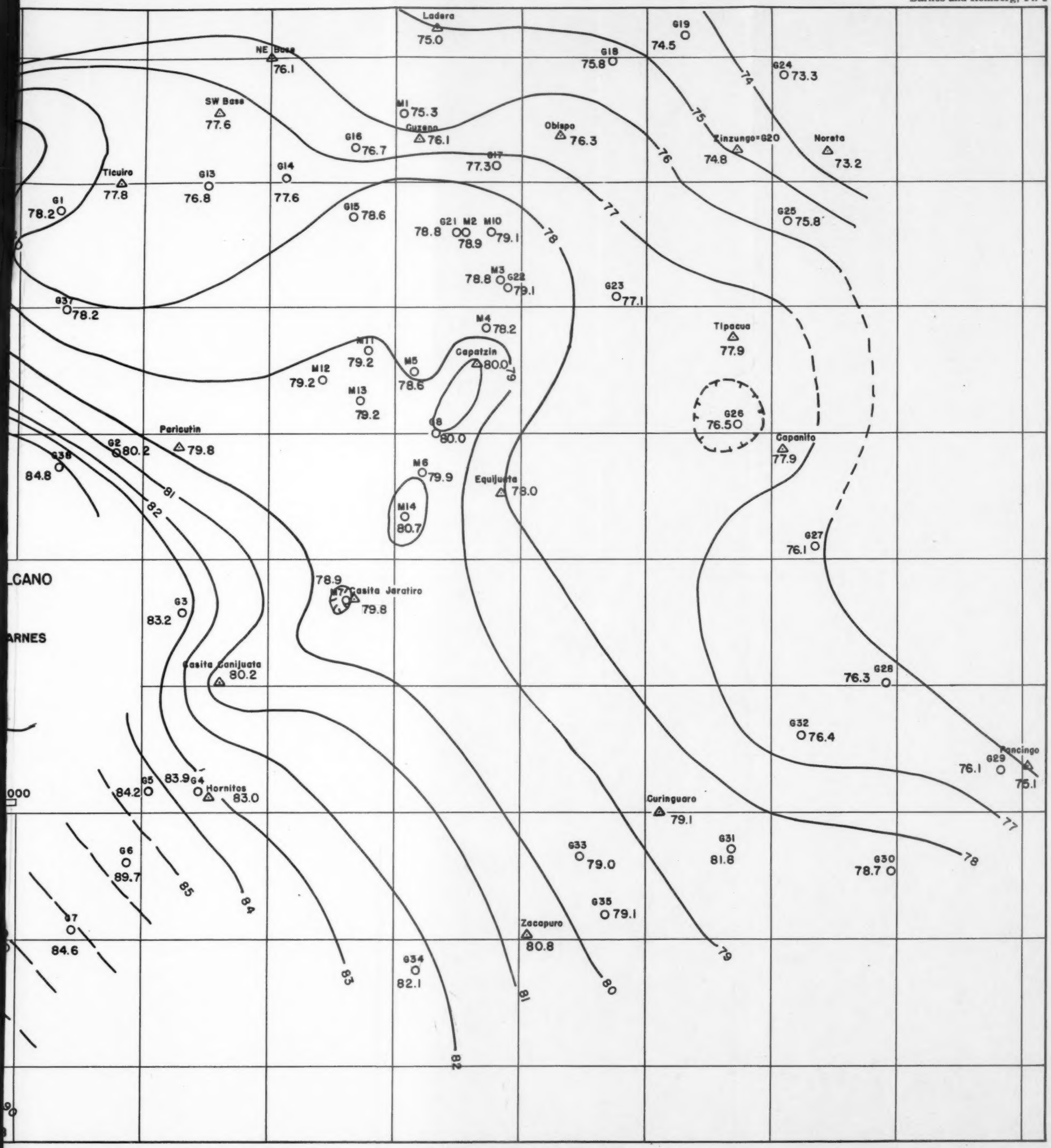

GRAVITATIONAL FORCE, PARICUTIN VOLCANO

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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GEOLOGY OF THE CONFUSION RANGE, WEST-CENTRAL UTAH

BY CHARLES S. BACON, JR.

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ABSTRACT

The Confusion Range, in west-central Utah between the House Range on the east and the Snake Range of Nevada on the west, is a folded mountain range which has been maturely dissected into hogbacks, strike valleys, and a few larger anticlinal valleys and synclinal ridges. At lower elevations are pediments, fans, and shore lines of Lake Bonneville.

The stratigraphic section includes an estimated 17,000 to 23,000 feet of sedimentary

strata ranging from Ordovician to Lower Triassic. The pre-Mississippian includes approximately 800 feet of lower dolomitic limestones, 300 feet of white quartzite probably equivalent to the Eureka of eastern Nevada, and an upper 3000 feet or more of dolomitic limestones. The Mississippian, 1825 feet thick, is a limestone section with a fauna strikingly comparable to that of the typical Mississippi Valley section. Near the base an upper Kinderhook zone carries abundant crinoids, and higher zones correspond to the Burlington, Keokuk, Moorefield, and Chester. The Pennsylvanian limestones, 1600 feet thick, also contain a midwestern fauna. The Permian, 8500 feet thick, is divided into a lower, sandy, and essentially nonfossiliferous facies, and an upper limestone facies carrying the *Punctospirifer pulcher* fauna typical of the Great Basin. The Lower Triassic, nine hundred feet thick, is dominantly shaly with thin limestone beds at intervals. It carries a prominent ammonite fauna. The youngest rocks in the area are small patches of Tertiary rhyolitic (?) and basaltic extrusives.

The range suffered strong eastward compression during the Cretaceous (?) or early Eocene (?). The axes of major folds are prominently arcuate, with probably some overthrusting and transverse tear faulting in the area of greatest axial curvature. No evidence of block faulting was observed.

INTRODUCTION AND ACKNOWLEDGMENTS

The Confusion Range of west-central Utah and its spur, the Conger Range, appear on the Fish Springs quadrangle as a complex system of prominent hogback ridges (Fig. 1). The wealth of stratigraphic and structural geologic problems implied by the morphology led the Texas Agricultural and Mechanical College field geology class to investigate the area during 5 weeks of the summer, 1941. The writer wishes to thank the college for the use of its equipment and facilities both in the field and on the campus, and C. L. Baker, head of the geology department at that time, for valuable criticisms and suggestions. He is grateful to M. L. Thompson, the late F. B. Plummer, L. R. Laudon, and J. M. Weller for paleontological identifications, and to Carey Croneis for access to the University of Chicago collection of Mississippian brachiopods in Walker Museum. The students who made the trip possible, and without whose excellent co-operation the area could not have been penetrated safely, share in the writer's gratitude. The war interrupted the exploration, but further study in the area is planned.

The Confusion Range, 50 miles long and 7–10 miles wide, lies between the House Range on the east and the Snake Range of Nevada on the west. It trends north, flanked by White Valley on the east and by Snake Valley on the west. The Conger Range, 10 miles long and 5 miles wide, is a spur which extends southwestwardly from Cowboy Pass where the Confusion Range is crossed by U. S. Highway 6. The nearest towns are Hinkley, 69 miles east, Delta, 74 miles east, and Baker, 38 miles west. The nearest habitations to Cowboy Pass are Foote's Ranch (14 miles) and Simonson's Ranch (18 miles); the nearest filling station is 32 miles away.

Drinking water and gasoline were obtained from Baker, Nevada, and hauled to the base camp. No spring water is available in the mountains during the summer, but in the spring months there is a little water at Conger and Skunk springs. The large and excellent Bishop Spring at Foote's Ranch, near the bottom of Snake Valley, is the only potable water. Knoll Spring, Tule Spring, and Coyote Spring are alkaline.

White Valley is 40 miles long and 10 miles wide and together with the Confusion

and House ranges makes up an area of 2000 to 2500 square miles without a permanent human resident. Summer temperatures are high, but the ever-present breezes and high evaporation rate make for good working conditions. Vegetation is sparse, with juniper present at higher altitudes. The expanse of the area, combined with its remoteness, aridity, and heat make exploration difficult.

HISTORY

Published information of the area is limited to three references by Gilbert (1875; 1890; 1928). The following quotations are from Gilbert (1875, p. 40, 120, 179).

"South of Dry Pass the case is reversed, and the continuation of the House Range, the Beaver Creek Range, and a number of small ridges known as the Confusion Range, show an easterly dip. In like manner, the Confusion Range at the west of the House and the Beaver Creek at the east, show no conspicuous eruptions. A small rhyolite flow was observed at the western base of the former, and a few basalt hills at the northern extremity of the latter. . . . They (Carboniferous strata) constitute a large part or the whole of the Confusion Range."

The easterly dip is erroneous. If one may speak of a prevailing dip, it is most likely westward, but the area is intricately folded, and the dips are correspondingly varied. There is much Permian and some Lower Triassic in addition to the Carboniferous in the northern part of the Confusion Range, and the southern third of the range is largely pre-Mississippian with small areas of Tertiary flows. The fault scarp noted by Gilbert (1890) was not recognized with certainty, but the well-defined shore lines which he traced around the Confusion Range indicate that it was a large peninsula in Lake Bonneville.

"The next mountain body to the west is the Confusion Range, an assemblage of small ridges, and associated with these a single scarp was found. This lies near Knoll Springs, on the east side of Snake Valley. It is low and worn, and follows the rock base closely." (p. 353)

"The Confusion Range east of Snake Valley, and the House Range east of White Valley, were massive peninsulas, joined at their southern extremities to the western shore of the lake." (p. 104)

Gilbert (1928, Pl. 31) does not mention the Confusion Range, but includes it on a map of the House and Fish Springs ranges.

PHYSIOGRAPHY

EROSIONAL FORMS AND DRAINAGE PATTERN

The relief of the area is produced by the mature dissection of folds into synclinal ridges and anticlinal valleys, with prominent lateral hogbacks separated by long strike valleys (Fig. 1). Most hogbacks are unbroken for considerable distances, but others are separated into flatirons by rather closely spaced gaps. The particularly prominent, straight hogback southeast of Cowboy Pass, designated here as Midridge, extends more than 9 miles in a N. 15° E. direction. Equally long but arcuate hogbacks reveal the curvature of the major axes of folding. The most prominent arc lies north of Cowboy Pass and is concave to the west with the curvature of a circle 6½ miles in radius. The arc is composed of two main lateral hogbacks separated by an arcuate valley about a mile wide. A 20- to 23-mile radius of curvature describes an arc which includes the northern portion of the Confusion Range and the Conger Range in the south.

Limestones and dolomites are most resistant to erosion; sandstones are generally friable and occur near ridge crests only where capped by limestone. Due to their low resistance, shales are topographically inconspicuous. In areas of steep dip

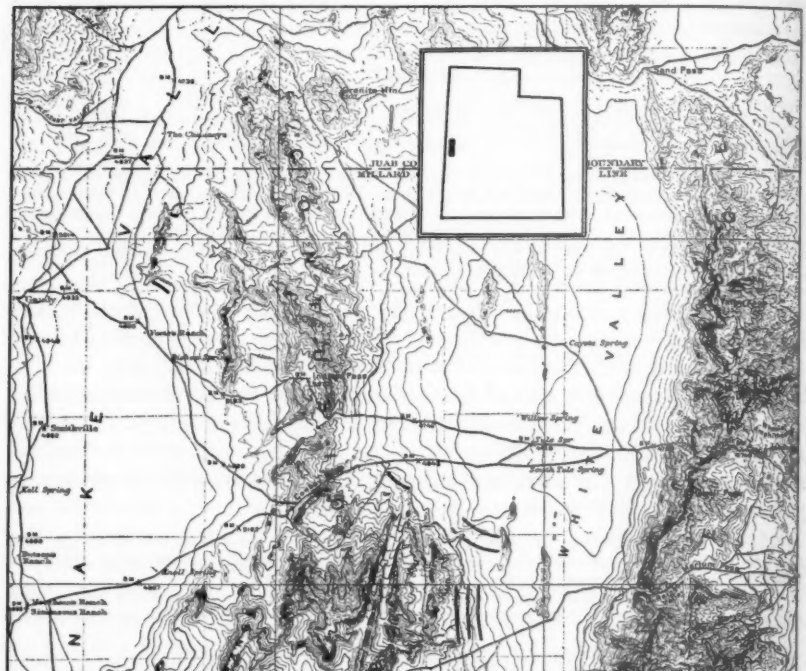

FIGURE 1.—*Index map and topography of the Confusion Range*
Portion of the Fish Springs quadrangle, with insert. With Lake Bonneville shore line features added

the weak beds occupy troughs or "devil's slides" flanked by prominent resistant layers. The canoe valleys of pitching anticlines are marked in a few places by domed resistant layers along the axial planes (windows). Erosion of such domes results in crescentic forms which are narrower or pointed in the direction of pitch, and which have arcuate cuestas connecting the lateral hogbacks of the up-pitch portions. Noses of plunging synclines, where occupied by resistant layers, are slightly hollowed,

steep-sided ridges with inward-dipping beds. Topographic ridges which are cut by transverse beds of unequal resistance have serrated crests.

A subsequent drainage pattern adjusted to the underlying rock structure characterizes the area. In the north-central part of T. 16 S., R 17 W., a channel 30 feet deep and 5 feet wide has formed along a 6-foot faulted offset of a resistant bed 40 feet thick, dipping 71° E. Along the Indian Pass road, the headwaters of the arcuate valley leading southwest into Snake Valley (bottom elevation 4850) have been turned eastward through a narrow canyon to White Valley (bottom elevation below 4400). The canyon northeast of Foote's Ranch is another case of piracy. It has deflected the drainage from the upper portion of the northwardly directed anticlinal valley southwestwardly across the strike of the beds. This canyon, not shown on the topographic map, is the one along which a portion of the Mississippian-Pennsylvanian section was measured.

Flanking the area of major relief are slopes partially of pediment and partially of alluvial-fan origin. No attempt was made to differentiate between them.

The bottoms of Snake and White valleys are playas, strongly alkaline and generally dusty. Shrub coppice dunes, composed of silt and fine sand and up to 10 feet high are locally developed on the playa surfaces.

LAKE BONNEVILLE SHORE LINES

Erosional wave-cut cliffs, notches or benches, and depositional beaches, bars, and hooks mark the outlines of the ancient Lake Bonneville. Although no effort was made to plot these features throughout the area, they are landmarks in certain places. The elevations were estimated from the topographic map.

Wave-cut benches were noted: (1) around all of the prominent ridges in White Valley north and south of Tule Springs, at approximately 4700 feet elevation; (2) on the west side of the prominent ridge in Snake Valley, T. 15 S., R. 18 W., at approximately 5100 feet elevation; (3) at the north end of Midridge where it disappears beneath the lake sediments and alluvium, at approximately 5100 feet elevation.

Depositional beaches, bars, and hooks were observed (Fig. 1): (1) at the north end of Midridge, elevation 5100 feet; (2) east of the mountains, T. 18 S., R. 15 W., elevation 4900, 5100, and 5200 feet; (3) east of the mountains, T. 17–18 S., R. 15 W., elevation 4600 feet and an upper level; (4) north of Foote's Ranch, T. 15 S., R. 18 W., elevation 5000 feet; (5) south of the Chimneys, T. 15 S., R. 18 W., elevation 5100 feet.

At several places the ancient shore lines are marked by white pebble coatings, as on the 5000–5100-foot shore line along the east side of the mountains roughly paralleling the CCC road to the government well in T. 15 S., R. 16 W. Several shore lines are visible along the west base of the House Range.

STRATIGRAPHY

GENERAL DISCUSSION

The stratigraphic section of the Confusion Range includes an estimated 16,000 to 24,000 feet of sedimentary rocks ranging from Ordovician to Lower Triassic. The oldest beds are in the southern part of the range, south of the Fish Springs

quadrangle. The Ordovician sponge *Receptaculites* has been collected from these beds (C. Beckwith, personal communication). However, the great fossil wealth discovered in the Mississippian and later sediments prompted a more detailed study

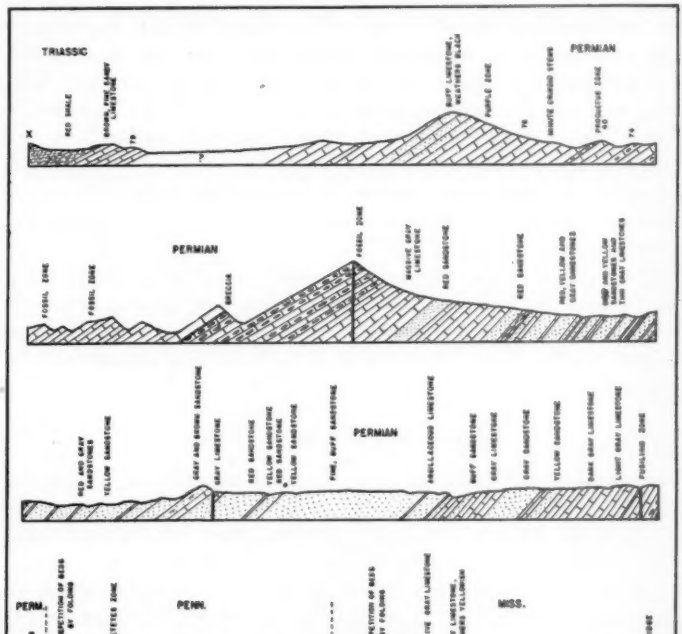

FIGURE 2.—*Cross section XY southeast of Cowboy Pass, T. 17 S., R. 16 W*
Numbers indicate fossil localities. Breaks in the section indicate offsets along the strike

of the central and northern part of the range where these deposits are located. The introduction of stratigraphic names and exact placement of contacts have been avoided because of the preliminary nature of the study. The cross sections and stratigraphic summaries by geologic periods give lithology, horizons of fossil localities (abbreviated FL), and structure (Figs. 2, 4). Determinations of contacts between the systems are tentative. Thicknesses of the pre Mississippian were estimated from topography and distances on the Fish Springs topographic sheet (Figs. 4, 5); all other thicknesses were measured (Fig. 2).

PRE-MISSISSIPPIAN

Locality: East face of the Confusion Range south of Cowboy Pass (Fig. 5, sections IJ and KL)

Lithology	*Thickness (Feet)*	
Dark-gray, dolomitic limestones. In part Mississippian and Devonian, probably also Silurian and Devonian. Approximately 3000 feet of strata rest on a white quartzite in T. 20 S., R. 15 W. FL 24, at the top of this section, is doubtfully correlated with FL 68. Stratigraphic thickness between FL 68 and 34, based on a 40 degree dip and no repetition of beds, is about 6000 feet. Maximum thickness between the white quartzite and the Mississippian at FL 34 might be 9000 feet. Actual thickness is probably 4000–4500 feet, similar to equivalent sections in the Gold Hill district, 60 miles to the north (Nolan, 1935), and the Pioche district 100 miles to the southwest (Westgate and Knopf, 1932). Fossil localities 41, 55, 24, 67, 68, and 69	3,000–9,000(?)	(Top)
White quartzite, probably equivalent to the Eureka quartzite of eastern Nevada (Westgate and Knopf, 1932; Hague, 1892; Nolan, 1935) and the Swan Peak of southeastern Idaho (Mansfield, 1927) and northern Utah (Richardson, 1913). Ordovician (?)	300–500	
Dark-gray dolomites and limestones. Ordovician (?)	800–900	(Base)
Total	4,100–10,400	

MISSISSIPPIAN

Locality: Southwest corner T. 17 S., R. 16 W. (Fig. 2)

Incomplete section. Base of Mississippian not determined

Lithology	*Thickness (Feet)*	
Massive, well-bedded, gray limestone	150	(Top)
Platy limestone which weathers yellowish brown, interbedded with 2 or 3 massive layers	100	
Medium-gray, massive, fossiliferous limestone. FL 29	25	
Moderately thin-bedded limestone	100	
Massive, gray limestone	50	
Dark, platy, coarse-grained limestone	90	
Platy limestone, dark gray on fresh explosure but weathering yellowish	450–460	
Beds concealed by alluvium. Limestone (?)	300	
Ridge-forming gray limestone	25–50	
Ferruginous limestone. Fossils weather out and occur scattered on the surface, especially in areas which are reddish to yellow brown. FL 31	85	
Thin-platy, argillaceous limestone, and dark-gray limestone which weathers yellowish. About in the middle is a 12-foot bed of massive, gray limestone	250	
Medium-gray limestone. FL 34	200–500(?)	(Base)
Total	1825–2160(?)	

Locality: Southwest quarter of T. 15 S., R. 17 W., east-northeast of Foote's Ranch (Fig. 3)

Incomplete section. Base of Mississippian not determined. An unexamined 1500–2000 feet of strata is exposed east of FL 22 but may not be entirely Mississippian (Fig. 5, section CD).

Lithology	Thickness (Feet)	
Massive, gray limtesone. Forms the "narrows" at upper end of the valley east-northeast of Foote's Ranch	20	(Top)
Coarse to dense, light- to dark-gray, and fossiliferous limestones. FL 28	40	
Platy limestone	50	
Black shale	25	
Sandy limestone weathered yellowish	75	
Calcareous gray sandstone (2 ft.), shell limestone, and buff limestone	25	
Red and yellow shale with *Pseudorthoceras*. FL 25	75	
Buff limestone; weathers yellowish brown. Beneath this is a black limestone that weathers to a pavement of rough, subrounded pieces. FL 43	220	
Agassizocrinus bed. FL 22	?	(Base)
Total	530	

The Mississippian in the Gold Hill district has a total thickness of 6400 feet (Nolan, 1935) and in the Pioche district of 2700 feet (Westgate and Knopf, 1932). The Mississippian in the Confusion Range is similar to the Pioche section but lacks the quartzitic sandstone member.

PENNSYLVANIAN

Locality: Southwest corner T. 17 S., R. 16 W. (Fig. 2)

Lithology	Thickness (Feet)	
Massive, gray limestone	200–250	(top)
Cherty, gray limestone with a zone rich in *Chaetetes* colonies	100	
Gray limestone	450	
Cherty limestone. Chert is dark gray, nodular, and weathers with rough, brownish-black surfaces, imparting to cherty limestone layers a conspicuously dark color. FL 35	275	
Gray limestone, with a cherty, fossiliferous zone in the middle. FL 66	375	
Light-gray, granular, fossiliferous limestone. FL 30 and 32	50–75	
Gray limestone	150	(Base)
Total	1600–1675	

Locality: Southwest quarter T. 15 S., R. 17 W., east-northeast of Foote's Ranch (Figs. 3, 5)
Incomplete section. Top of Pennsylvanian covered by alluvium

Lithology	Thickness (Feet)	
Massive, gray limestone with *Chaetetes* colonies	25–50	(Top)
Cherty limestone which weathers yellowish	25	
Platy, gray limestone	60	
Massive, medium-gray limestones with numerous cherty layers and color variations	725	
Fossiliferous limestone and coral bed. FL 16	15–25	
Cherty, gray limestone	50	
Massive, gray to yellowish-brown limestone with some cherty and fossiliferous zones. FL 27 and 57	560	(Base)
Total	1490	

PERMIAN

Locality: Southwest corner T. 17 S., R. 16 W. (Fig. 2)
Section not quite complete, the top 500 feet (?) covered by alluvium

Lithology	Thickness (Feet)
Concealed by alluvium	500 (?) (Top)
Grayish-brown to buff, somewhat banded and arenaceous limestone. Weathers black. Fluted surfaces due to differential weathering	550
Purplish limestone containing abundant minute gastropods	250
Massive, gray limestones with at least 5 prominent fossil horizons. Near the top is a 175-foot bed characterized by abundant slender crinoid stems. At the base is a 4-foot breccia containing limestone and quartzite fragments. FL 76, 40 and 74	1725
Massive, cherty, gray limestone, somewhat arenaceous near the top. Prominent ridge maker. Measured section offset along strike 175 feet from top	475
Massive, gray limestone containing smaller crinoid stems	400
Red sandstone. A 10–30-foot gypsum bed near line of section should appear here, but may be concealed by overburden. Strike fault at base of this member may explain repetition below of 500 feet of similar section	100–125
Massive, gray limestone with crinoid stems	400
Red sandstone	100
Red siltstone or shale	60
Red, yellow, and gray sandstones intercalated with numerous thin, gray limestone beds. Red and yellow predominate at top, gray at base. Some sandstones quite friable. Some limestones platy	925
Red, yellow, and gray sandstones with few intercalated, thin, gray limestone beds	825
Massive, gray limestone. Section offset at base of limestone due to recognized fault	75
Red, buff, and yellowish sandstones with almost no limestone beds	1460
Interbedded gray and buff sandstones with gray limestone	660–675
Light- and dark-gray, massive limestones. Prominent fusilinid zone 175 feet above base. Section offset along fusilinid zone	725
Massive, cherty, gray limestone with prominent coral zone. FL 78	175 (Base)
Total	9030
Total after correction for duplication of beds	8500

In the Gold Hill district, the Pennsylvanian-Permian contact is in the Oquirrh formation (Nolan, 1935). The combined thickness of the Pennsylvanian and Permian is 9100 feet as compared to 10,000 feet in the Confusion Range.

TRIASSIC

Locality: T. 16 S., R. 16 W. along eastern edge of mountains (Fig. 5, section EF)

Lithology	Thickness (Feet)
Thin-platy, brownish-gray, terebratulid limestone. FL 53	22 (Top)
Shale	13
Thin-platy, black limestone	9
Yellow and red shale	144
Limestone	2
Red shale	90
Brownish limestone	4
Red shale	60
Brownish-green limestone with abundant *Aviculopecten*. FL 50	5
Red shale with a few thin limestone beds	65
Platy, yellowish limestone with 2-foot limestone bed at top	69
Gray and brown limestone	72
Shale	343
Ammonite bed. Brownish limestone. FL 15	5 (Base)
Total	903

Locality: T. 17 S., R. 16 W. at FL 79 (Fig. 2)
Incomplete section, base covered by alluvium

Lithology	Thickness (Feet)
Thin-platy, fine-sandy limestone	? (Top)
Red shale	275
Brown, very fine-sandy limestone	40
?	80
Platy, greenish limestone with abundant *Aviculopecten*. FL 79.	125 (Base)
Total	520

The Confusion Range section is predominantly calcareous, but the outstanding stratigraphic feature of the area is the great thickness of sandstones in the lower Permian, and the alternation of these sandstones with limestone members. The entire Paleozoic section carries less shale than the Lower Triassic.

The occurrence of gypsum in the Permian is to be expected and was found (1) in T. 17 S., R. 16 W. at the end of section GH; (2) at the base of the ridge on the south side of Cowboy Pass; (3) on the Indian Pass anticline along section GH; (4) on the west side of the syncline between Middle and East anticline along section CD; (5) in T. 14 S., R. 17 W. in the large valley west of the road and facing Granite Mountain. At the last place, the gypsum is 30 feet thick and lies at the base of a thin-bedded succession of yellow, red, and pink sandstones alternating with black and gray, phosphatic limestones, 170 feet below the massive upper Permian limestones. Beneath the gypsum are sandstones similar to those of the measured section in T. 17 S., R. 16 W. The first and fifth gypsum beds may therefore be correlated with reasonable certainty; the other occurrences cannot be correlated.

A somewhat transitional fauna masks the Mississippian-Pennsylvanian contact and accounts for the repetition of certain guide fossils. In T. 17 S., R. 16 W. the contact is tentatively placed 150 feet below FL 30 and 32. In T. 15 S., R. 17 W., it is placed at the top of the massive, gray limestone which forms the "narrows" at the upper end of the valley east-northeast of Foote's Ranch.

The Pennsylvanian-Permian contact is placed at the base of the cherty limestone containing the Permian FL 78. No fossils were found in the underlying 200 feet of massive, gray limestone, but immediately below that is a *Chaetetes* zone of Pennsylvanian age. There is no faunal transition at this contact.

The Permo-Triassic contact in T. 16 S., R. 16 W., is placed at the base of the ammonite bed, where there is a striking faunal and lithologic change. The Permian between the contact and FL 44 includes 225 feet of purplish limestone, 40 feet of red shale, and 625 feet of massive, gray limestone. The overlying Triassic is dominantly shale with thin limestone members. In T. 17 S., R. 15 W., the Permo-Triassic contact is concealed beneath alluvium.

TERTIARY AND QUATERNARY

Rhyolite and tuff occur in the southern part of the range, the largest area in King's Canyon and another east of the Conger Range. They are probably remnants of more extensive Tertiary flows and ash deposits.

Recent basaltic lava flows and cinder cones were observed at the extreme northern end of the range, but the cones were not visited.

PALEONTOLOGY

GENERAL STATEMENT

The Confusion Range offers an unusual opportunity for study of the Great Basin faunal history because of its great stratigraphic range, Ordovician to Lower Triassic. The 1941 study yielded approximately 250 fossil species collected mainly from Mississippian and younger strata.[1] The Mississippian and Pennsylvanian collections bear a close relation to the typical Mississippi Valley faunas. A map gives the fossil localities (Fig. 3), and faunal lists of the localities are grouped by geological periods.

PRE-MISSISSIPPIAN

The pre-Mississippian strata yielded very little fossil material. The best assemblage is from the Devonian (?) FL 69 with *Atrypa* sp., a discoid coral (*Propites* ?), several gastropods, and a few other fossils (Table 1). A doubtful correlation of FL 24 and 68 is based upon the occurrence in both places of numerous small gastropods of the genus *Lophospira* (?).

MISSISSIPPIAN

The oldest clearly defined horizon is the Lower Mississippian Midridge limestone at FL 21. It is a crinoidal bed carrying abundant Cactocrinus arnoldi, Platycrinus cf. graphicus, and Dichomultiple x Laudon[2] in addition to other crinoids, brachiopods, gastropods, and trilobites. It is of upper Kinderhook age and closely akin to the crinoidal beds in the Bozeman area of Montana. The Bristol Pass of the Pioche district carries *Platycrinus* sp. and may also be equivalent (Westgate and Knopf, 1932). The relation of this stratigraphic member to the Madison of the Gold Hill district (Nolan, 1935) and of other areas is not established.

The Burlington is probably represented by the limestone at the north end of Midridge, at FL 34, where *Athyris lamellosa*, *Dictyoclostus burlingtonensis*, *Spirifer grimesi*, and *Spirifer carinatus* are the most typical brachiopods.

The Keokuk is represented by FL 39 which contains *Productus viminalis*, *Productus crawfordsvillensis*, *Spirifer logani*, and *Composita glabra*.

The Middle Mississippian at FL 22, 23, and 31 is of early Meramec age. It is characterized by *Agassizocrinus* cf. *conicus*, *Leiorhynchus carboniferum*, *Lyrogoniatites newsomi*, *Neoglyphioceras entogonum*, and *Neoglyphioceras subcirculare* and abundant pilecypods and gastropods. This member is equivalent to the Helms, New Mexico, the Cowley, Kansas, and the Moorefield of Oklahoma and Arkansas. In the Great Basin it can be correlated with the White Pine of the Eureka district (Hague, 1892), the Peers Spring (?) of the Pioche district (Westgate and Knopf, 1932), and parts of the Brazer in southeastern Idaho (Mansfield, 1927) and Randolph,

[1] The large number of fossils prevented distribution of the entire collection to paleontological specialists. However, M. L. Thompson identified the fusilinids, L. R. Laudon the crinoids, F. B. Plummer the goniatites, and J. M. Weller the meager trilobite fragments. The remainder of the fossils were checked and rechecked several times against published descriptions and illustrations, and against the University of Chicago paleontological collection in Walker Museum (Boutwell, 1912; Branson, 1916; Croneis, 1930; Dunbar and Condra, 1932; Girty, 1903, 1909, 1910, 1911, and 1920; Hall and Whitfield, 1877; King, 1930; Knight, 1941; Mansfield, 1927; Mather, 1915; Mathews, 1929; Meek, 1876, 1877; Plummer and Scott, 1937; Shimer and Shrock, 1944; Smith, 1903 and 1932; Weller, 1914).

[2] Crinoid determinations and stratigraphic placement by L. R. Laudon.

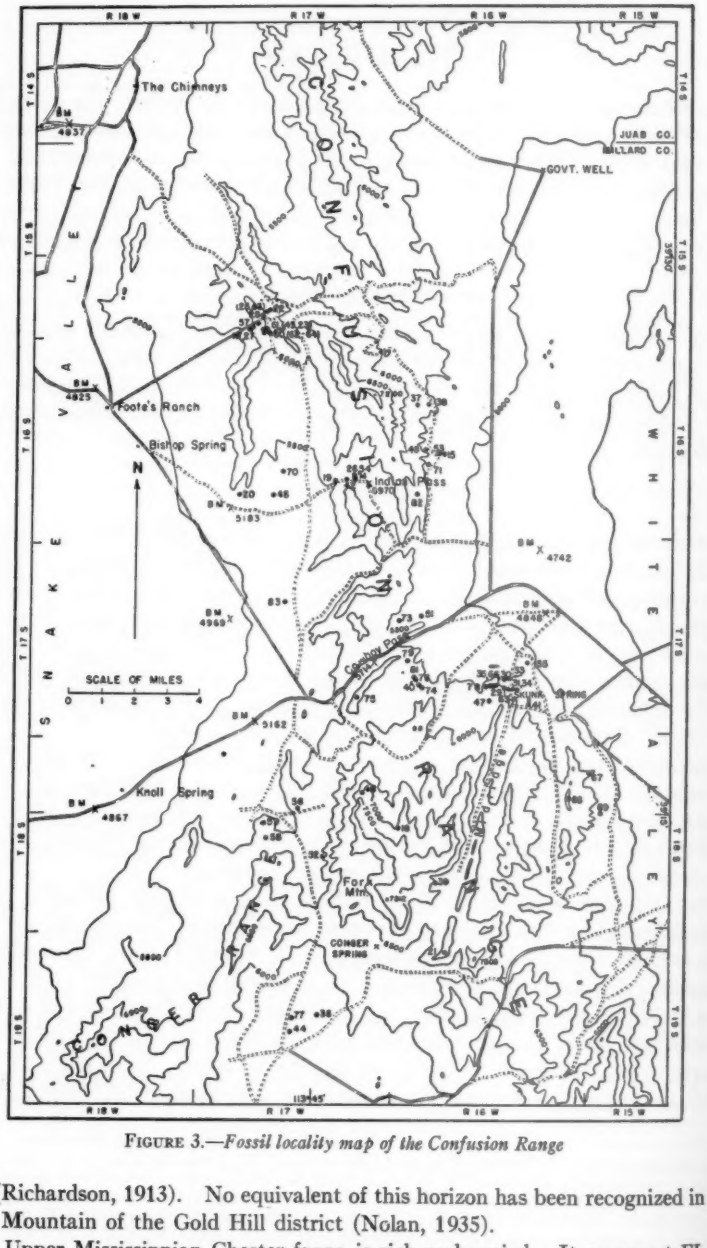

FIGURE 3.—*Fossil locality map of the Confusion Range*

Utah (Richardson, 1913). No equivalent of this horizon has been recognized in the Ochre Mountain of the Gold Hill district (Nolan, 1935).

The Upper Mississippian Chester fauna is rich and varied. It occurs at FL 25,

28, 29, 33, 43, 45, 60, 61, 65, and 70. Typical fossils are *Cleiothyridina sublamellosa, Diaphragmus elegans, Dictyoclostus inflatus, Eumetria acuticosta, Girtyella indianensis, Linoproductus ovatus, Punctospirifer transversa, Reticulariina spinosa, Spirifer leidyi, Stenoscisma explanata,* and *Triplophyllum spinulosum.* This horizon may be

TABLE 1.—*Pre-Mississippian fossils*

Names	Fossil Localities					
	24	41	55	67	68	69
Brachiopods						
Atrypa sp.						x
Rhipidomella sp.						x
Cephalopods						
Orthoceras sp.						x
Corals				x		
Amplexus sp.						x
Favosites sp.		x				x
Propites sp.						?
Stromatoporoid		?	?			
Syringopora sp.					x	
Gastropods				x		
Euconia sp.						x
Hormatoma sp.						x
Lophospira sp.	x				x	x
Meekospira sp.						x
Trochonema sp.						x
Pelecpods						
Nucula sp.						x
Sponges	?	?		?		
Unidentified tubular and conical markings	x	x				

equivalent to the Herat shale member of the Ochre Mountain in the Gold Hill district (Nolan, 1935, p. 30–31), the White Pine of the Eureka district (Hague, 1892), and the upper part of the Brazer in southeastern Idaho (Mansfield, 1927, p. 68).

FL 29 is the lowest horizon with *Spirifer occidentalis* and consequently may be considered Lower Pennsylvanian. The other forms at this locality, however, are Mississippian, as are the fossils at FL 33 which is stratigraphically equivalent or higher. Further study may show that the Mississippian-Pennsylvanian contact should be just below FL 29 instead of above as presented here.

In the area northwest of Foote's Ranch the Pennsylvanian brachiopod *Juresania nebrascensis* occurs at FL 28 with typical Chester forms such as *Cleiothyridina sublamellosa, Linoproductus ovatus, Punctospirifer transvera* and *Triplophyllum spinulosum.* A common brachiopod here is *Schizophoria cf. resupinata Mart.*, which resembles the Carboniferous specimens from Visé, Belgium. The Utah specimens

TABLE 2.—*Mississippian fossils*

| Names | Fossil Localities | | |

TABLE 2.—*Continued*

Names	Fossil Localities																			
	21	22	23	25	28	29	31	33	34	39	43	45	60	61	65	70				
Bryozoans																				
Fenestella sp.						x			x				x			x				
Rhombopora lepidodendroides Meek					x															
Tabulipora sp.					x															
Cephalopods																				
Cravenoceras sp.								x												
richardsonianum (Girty)		x				x														
Dimorphoceras cf. *gilbertsoni* Phillips						x														
Lyrogoniatites newsomi (Smith)						x	x													
Neoglyphioceras entogonum (Gabb)						x														
subcirculare (Miller)						x														
Orthoceras sp.								x												
sp. A Girty						x														
Pseudorthoceras knoxense Girty			x			x					x									
Corals																				
Amplexus sp.					x															
Chaetetes sp.						x														
Dibunophyllum sp.																x				
Favosites cf. *divergens* White and Whitfield																x				
Lithostrotion sp.									x				x							
Lithostrotionella cf. *americana* Hayaseka									x											
Triplophyllum spinulosum (Edwards and Haime)	x				x						x		x	x						
Zaphrentis sp.								x												
cf. *excentrica* Meek						x														
Crinoids																				
Agassizocrinus sp.		x	x																	
cf. *conicus* Owen and Shepard		x	x																	
Arocrinus immaturus (Wachsmut and Springer)	x																			
Cactocrinus arnoldi (Wachsmut and Springer)	x																			
opusculus Hall	x																			
cf. ornatissimus	x																			
Dichomultiple x Laudon	x																			
Eretmocrinus tentor Laudon	x																			
Goniocrinus sp.?											x									
Pedalotrypa	x																			
Platycrinites cf. *graphicus* (Hall)	x																			
cf. Huntsvillae (Troost)	x																			
Gastropods																				
Bellerophon sp.		x	x	x		x														
crassus var. *wewokanus* Girty				x																
Capulus sp.	x																			
Euphemus carbonarius Cox				x																
Macrocheilus sp.		x																		
Platyceras sp.	x																			
Pleurotomaria cf. *pealeana* Girty		x																		
Worthenia tabulata (Conrad)			x																	

TABLE 2.—*Concluded*

Names	Fossil Localities									
	21	22	23	25	28	29	31	33	34	39
Pelecypods										
Allorisma walkeri var. *abreviatum* Girty							x			
Astartella sp.		x	x							
Caneyella percostata Girty							x			
Leda vaseyana McChesney							x			
Nucula anodontoides Meek				x			x			
rectangula McChesney										
Solenopsis cf. *nitida* Girty							x			
Yoldia glabra Beede and Rogers				x						
Scyphozoans										
Conularia cf. *crustula* White							x			
Sponges										
Wewokella solida Girty										
Trilobites										
(Genus?) *loganensis*	x									
Kaskia chesterensis Weller and Weller						x				

Names	Fossil Localities									
	43	45	60	61	65	70				
Pelecypods										
Allorisma walkeri var. *abreviatum* Girty										
Astartella sp.										
Caneyella percostata Girty										
Leda vaseyana McChesney		x								
Nucula anodontoides Meek										
rectangula McChesney		x								
Solenopsis cf. *nitida* Girty										
Yoldia glabra Beede and Rogers										
Scyphozoans										
Conularia cf. *crustula* White										
Sponges										
Wewokella solida Girty	x									
Trilobites										
(Genus?) *loganensis*										
Kaskia chesterensis Weller and Weller										

are generally thicker and have a more pronounced sinus in the anterior portion of the pedicle valve. They approach *Schizophoria resupinoides* Cox of the Lower Pennsylvanian but have somewhat thicker pedicle valves. The Mississippian-Pennsylvanian contact is tentatively placed above FL 28 because of the dominantly Mississippian aspect of the fossil assemblage.

The fossils at FL 25 compare with the Wewoka fauna of Lower Pennsylvanian age, but they are long-range forms also found in the Upper Mississippian.

The overlap of certain guide fossils across the Mississippian-Pennsylvanian contact is regarded as evidence of a moderate faunal transition (Bissell and Hansen, 1935).

PENNSYLVANIAN

The lower Pennsylvanian of FL 30 and 32 is typified by: *Composita argentea, Crurithyris planoconvexa, Dictyoclostus portlockianus, Eumetria acuticosta, Girtyella indianensis, Orbiculoidea capuliformis, Rhipidomella* cf. *michelini*, and *Spirifer occidentalis*. The assemblage is definitely Pennsylvanian, with two transitional types, *Eumetria* and *Girtyella*. In the area east-northeast of Foote's Ranch (FL 57, 27, and 16) the typical assemblage is *Cleiothyridina orbicularis, Composita subtilita, Hustedia mormoni, Juresania nebrascensis, Linoproductus ovatus, Linoproductus prattenianus, Reticulariina spinosa, Rhipidomella penniana, Spirifer occidentalis, Rhombopora lepidodendroides, Tabulipora* sp., *Batostomella* sp., and *Lithostrotion* sp. *Linoproductus ovatus* and *Reticulariina spinosa*, carry over from the Mississippian; *R. spinosa* is one of the most characteristic fossils of FL 16. The *Rhipidomella penniana* is identical with plesiotypes from the Upper Carboniferous of Itaituba, Brazil, and has a similar medial

TABLES 3.—*Pennsylvanian fossils*

| Names | Fossil Localities | | |

TABLE 3.—*Continued*

Names	Fossil Localities											
	16 20	27 30	32 35	36 44	46 47	48 52	57 62	63 64	66 75	77
Crinoids										
Aatocrinus sp.	x									
Crinoid stem 4 cm. in diameter		x								
Bryozoans										
Batostomella sp.						x	x			
Fenestella sp.		x								
Fistulipora sp.								x	x	
Rhombopora lepidodendroides Meek	x									
Tabulipora sp.	x	x	x						x	
Cephalopods										
Glaphyrites cf. *hyattianus* (Girty)								x		
Orthoceras sp.							x			
Pseudorthoceras knoxense (McChesney)								x		
Corals										
Caninea cf. *torquia* (Owen)					x	x				
Chaetetes milleporaceous Troost	x					x				
Lithostrotion sp.	x									
Triplophyllum spinulosum (Edwards and Haime)				x		x		x		
Syringopora sp.				x	x					
Gastropods										
Euphemus carbonarius Cox							x			
Phanerotrema grayvillense Norwood and Pratten								x	x	
Sphaerodoma brevis White								x		
Worthenia tabulata (Conrad)							x			
Pelecypods										
Astartella concentrica Conrad							x			
Deltopecten cf. *texanus* Girty		x								
Leda bellistriata Stevens								x		
Nucula sp.								x		
anodontoides Meek							x	x		
wewokana Girty							x			
Nuculoposis ventricosa Hall								x		
Pleurophorus sp.		x								
Sponge		x								
Trilobites										
Ditomopyge sp.						x				

sinus in the brachial valve and a trapezoidal to subtriangular outline. The *Rhipidomella cf. michelini* is larger and more ovoid; it is characteristic of FL 30 and 36. *Composita* is widespread throughout the Mississippian and Pennsylvanian, but a dis-

tinction between *C. subquadrata* and *C. subtilita* is hardly possible. The two forms are consequently of no value as guide fossils.

The fossiliferous lower Pennsylvanian of the Confusion Range probably corresponds to the Manning Canyon and lowest Oquirrh (?) of the Gold Hill district (Nolan, 1935) and Oquirrh Mountains (Gilluly, 1932), to the upper part of the Bailey Spring in the Pioche district (Westgage and Knopf, 1932), and to the Wells in the Randolph area (Richardson, 1913) and in southeastern Idaho (Mansfield, 1927).

PERMIAN

The lower Permian at FL 78 contains *Composita mira*, *Marginifera haydenensis*[1] and *Punctospirifer laxa*. *Marginifera haydenensis* is the equivalent of *M. capaci* (d'Obigny) described from the Wolfcamp of Texas (King, 1930, p. 86). A fusilinid zone occurs 200 feet above FL 78, but the specimen collected from the fusilinid bed was lost. No fossiliferous zone was found in the limestones between the fusilinid bed and the sandstone section. The lower Permian of the Confusion Range corresponds to the prevailingly sandy, central facies of the Oquirrh formation in the Gold Hill district (Nolan, 1935, p. 34–35).

The typical Upper Permian fossils found at FL 18, 19, 37, 38, 40, 59, and 70, are *Avonia subhorrida*, *Composita mira*, *Neospirifer pseudocameratus*, *Productus multistriatus*, *Punctospirifer hilli*, *Punctospirifer pulcher*, *Pustula nevadensis*, and the fusilinids *Pseudoschwagerina*, *Schwagerina*, and *Schubertella kingi*. The presence of *S. kingi* at FL 59 places this horizon above the Neva limestone of Kansas[1].

The upper Permian of the Confusion Range is characterized by the *Punctospirifer pulcher* (*Spiriferina pulchra*) fauna and corresponds to the Gerster of the Gold Hill district (Nolan, 1935, p. 40), the Park City of the Wasatch Mountains (Boutwell, 1912), the Phosphoria of southeastern Idaho (Mansfield, 1927, p. 75–81) and of Randolph, Utah (Richardson, 1913), and the Arcturus of the Ely district (Spencer, 1917). The fusilinid zones are correlated with the *Schwagerina* and *Pseudoschwagerina* zones of the upper and highest Oquirrh in the southern Wasatch Mountains (Bissell, 1939) and are regarded as Wolfcamp in age.

LOWER TRIASSIC

The Lower Triassic of the Confusion Range is characterized by an ammonite fauna with abundant: *Inyoites oweni*, *Juvenites dieneri*, *Lecanites knechti*, *Meekoceras muschbachanum*, *Pseudosageceras multilobatum*, and *Xenodicus nivalis*. The ammonites appear to be concentrated in a thin limestone bed at the base of the Triassic. About 550 feet higher in the section is a thin bed with abundant *Aviculopecten*, *Gervillea*, *Schizodus*, and *Laevidentalium*. A terebratulid horizon is an additional 325 feet higher, at the top of the Triassic in the area.

In the Gold Hill district the Lower Triassic carries a *Meekoceras* fauna, and the total thickness is only 50 feet (Nolan, 1935). In southeastern Idaho the Lower Triassic is divided into the Woodside shale and the overlying Thaynes group, with the *Meekoceras* zone at the base of the Thaynes. The Triassic from the Cottonwood-

[1] Fusilinid identifications and stratigraphic placement by M. L. Thompson.

TABLE 4.—*Permian fossils*

Name	Fossil localities													
	18	19	26	37	38	40	42	49	54	56	58	59	74	76	78	83
Brachiopods																
Aulosteges hispidus Girty				x												
Avonia subhorrida (Meek)				x	x	x								x		
Chonetes granulifer Owen											x					
Composita mira Girty				x	x	x										x
parva C. Branson				x					x			x	x			
plana C. Branson				x												
subtilita (Hall)				x												
Dictyoclostus portlockianus (Norwood and Pratten)									x							
Dielasma phosphoriensis C. Branson				x												
schucherti minor King					x											
Echinoconchus semipunctatus (Shepard)		x														
Hustedia phosphoriensis C. Branson				x												
Linoproductus cora (d'Orbigny)		x														
Marginifera sp.	x						x		x							
capaci (d'Orbigny)		x														x
wabashensis (Norwood and Pratten)											x					
Neospirifer pseudocameratus (Girty)		x		x	x	x			x		x	x		x		
Orbiculoidea utahensis Meek							x					x				
Productus multistriatus Meek		x		x	x	x		x	x		x			x		
phosphaticus Girty											x					
semireticulatus hermosanus Girty												x				
Punctospirifer hilli (Girty)				x	x									x		
laxa (Girty)																x
pulcher (Meek)				x	x	x			x					x	x	
pulcher var. *alatus*					x	x										
Pustula nevadensis Meek		x		x	x	x		x	x		x			x		
Spirifer sp.	x															
Bryozoa																
Batostomella sp.			x	x	x									x		
Fenestella sp.	x			x	x											
Fistulipora carbonaria Ulrich							x									
Polypora sp.					x		x									
Corals																
Campophyllum sp.						x										
Syringopora sp.	x									x						
Echinoids																
Echinocrinus cf. *aculeata* (Shumard and Swallow)									x		x					
Fusilinids																
Pseudoschwagerina sp.												x				
Schubertella kingi Dunbar and Skinner												x				
Schwagerina sp.	x		x													
Gastropods																
Capulus sp.						x										
Merostomes																
Protolimulus or *Prestwichia*						x										
Pelecypods																
Aviculopecten sp.				x												
Tribobites			x													

Park City district (Boutwell, 1912) and the San Francisco district (Butler, 1913) are also approximate equivalents.

TABLE 5.—*Lower Triassic fossils*

Name	Fossil localities							
	15	50	51	53	71	72	73	79
Bone fragment	x							
Brachiopods								
Composita sp.					x			
Terebratula thaynesiana Girty		x		x			x	
Cephalopods								
Anasibirites desertorum Smith	x							
smithi Mathews	x							
Aspenites acutus Hyatt and Smith	x							
Clypeoceras pusillum Smith	x							
Columbites parisianus Hyatt and Smith	x							
Inyoites oweni Hyatt and Smith	x							
Juvenites dieneri Hyatt and Smith	x					x		
Lecanites knechti Hyatt and Smith						x		
Meekoceras (Koninckites) muschbachanum White	x							
Orthoceras sp.	x							
Pseudosageceras multilobatum Noetling	x							
Thermalites thermarum Smith	x							
Xenodiscus nivalis Diener	x							
Gastropods								
Macrocheilus cf. *anguliferus* White	x					x		
Pelecypods								
Aviculopecten deseret Girty	x	x		x				?
cf. *utahensis* Meek			x					
Gervillea (Bakewellia) cf. *ceratophaga* Schloth	x	x			x			
Schizodus cf. *obscurus* Sow		x						
Scaphopods								
Laevidentalium sp.	x	x						

STRUCTURE

Structurally the Confusion Range is a complex mass of major and minor folds, the former with strikingly arcuate axes most sharply curved in the area north of Cowboy Pass (Fig. 4). The plunge of these structures is toward the area of sharpest axial curvature—southeast in the northern mountains and northeast in the southern mountains. The tightest folding is also mostly in this area.

A set of six transverse sketch sections illustrates the general structure of the mountains. Topography is to scale, but bedding lines are solely for the purpose of illustrating the structures and do not represent actual contacts or thicknesses (Fig. 5).

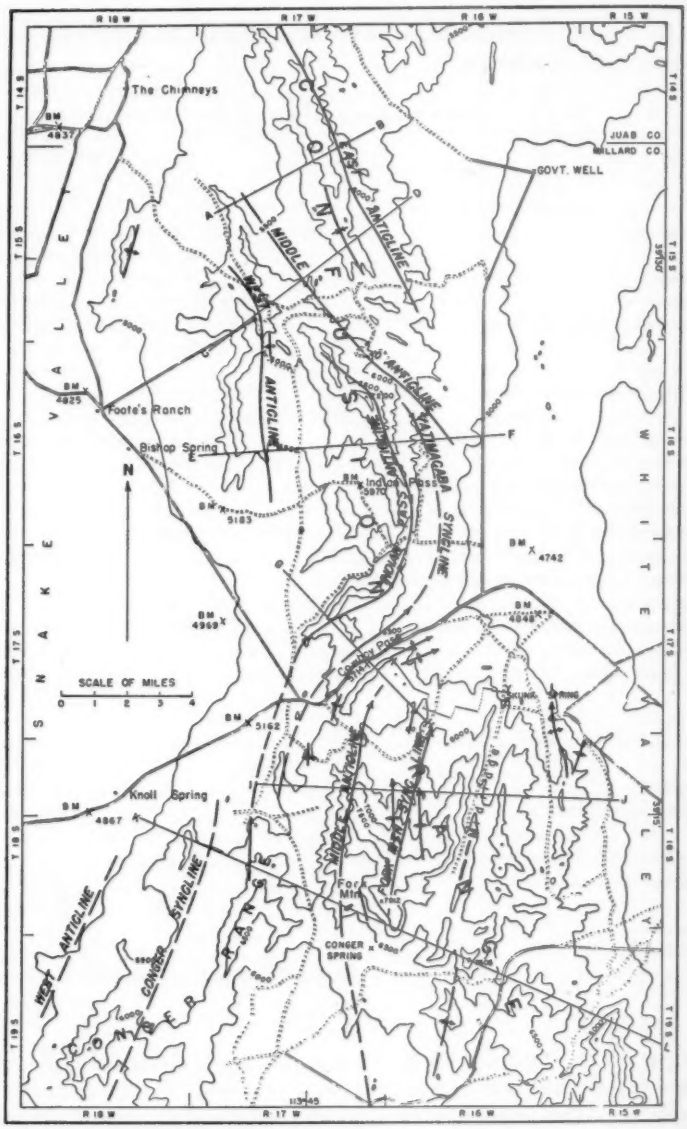

FIGURE 4.—*Structure map of the Confusion Range*

With location of the cross section XY and the sketch sections indicated

Section AB shows steep to vertical beds on the west flank of the Middle anticline and a striking group of yellow beds appearing on opposite sides of the anticlinal valley. The sharply folded East syncline was not traced westward.

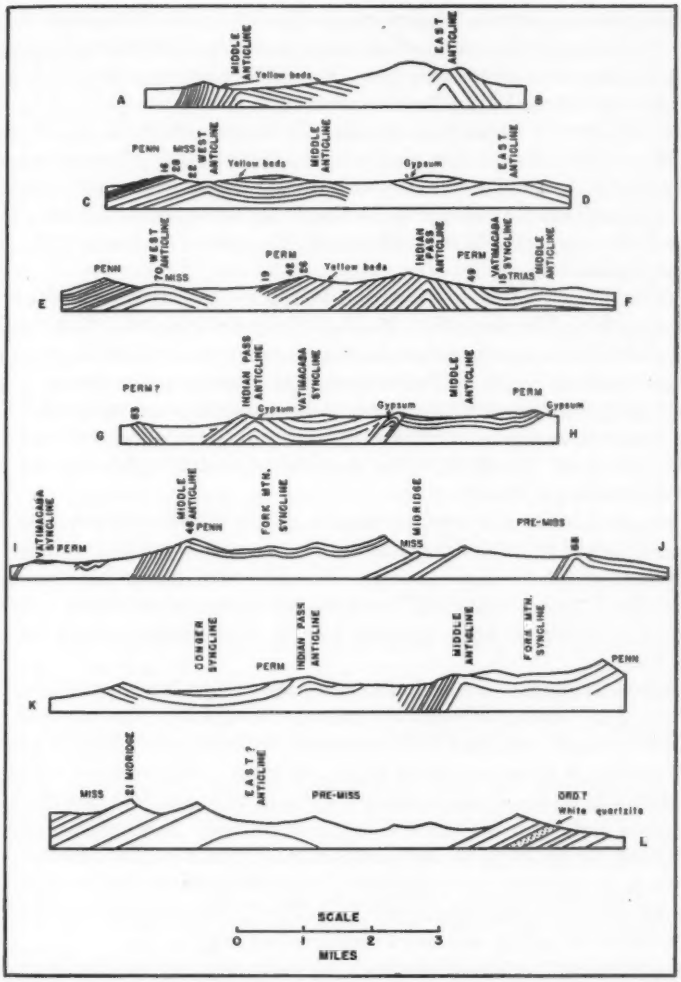

FIGURE 5.—*Sketch sections of the Confusion Range*
Numbers give fossil localities

Section CD includes the measured section east-northeast of Foote's Ranch already described. The broad West anticline occupies a conspicuous anticlinal valley on the west side of which is the Agassizocrinus zone. The yellow beds correspond to those of section AB. To the east are the Middle and East anticlines, both less sharply flexed than farther north. The gypsum may correspond to the 30-foot bed west of Granite Mountain.

Section EF cuts the West and Indian Pass anticlines and the Vatimacaba syncline which includes the Triassic section described earlier. The fusilinid zone is above the

Permian sandstones, but the fusilinid zone in T. 17 S., R. 16 W. is below the sandstones. Consequently these two beds are not equivalent. The yellow sandstone beds probably correspond to those of sections AB and CD. It seems likely that a thrust fault occurs west of the Indian Pass anticline, as shown.

Section GH cuts the Indian Pass anticline, the Vatimacaba syncline, and the Middle anticline. The three thrusts may be shear faults resulting from stronger eastward thrust slightly north of this section. If the Permian in the area contains only a single gypsum bed, the bed will be a valuable horizon marker. There is no proof that this is the case, but it is not unlikely that the three occurrences in this section are age equivalents.

In section IJ, the striking, asymmetrical Middle anticline is the same structure as the low open fold of section GH. The fold plunges northward. Eastward is the broad Fork Mountain syncline which has been squeezed at the north so as to produce two minor anticlines within. The Mississippian-Pennsylvanian contact is not far above the goniatite zone (FL 31). Very little information was gathered about the massive limestone section east of Midridge, but it is believed to be largely pre-Mississippian. The lower east flank of the easternmost anticline yielded a few poorly preserved Devonian (?) fossils.

The long section KL includes the Conger syncline, Middle anticline, Fork Mountain syncline, and a broad anticline that may correspond to the East anticline in the northern part of the Confusion Range. The structural interpretation across the East anticline is grossly simplified, but gives the general stratigraphic relation between the Ordovician (?) white quartzite and the Mississippian crinoid zone of the measured section.

The structural picture of the Confusion Range is therefore an eastwardly compressed, complex mass of sedimentary strata, more than 17,000 feet thick, which yielded with unequal resistance to the compressive stresses, resulting in the present intricate pattern of major and minor folds, and faults. The period of folding probably corresponds to the second structural cycle in the Gold Hill district, which is Cretaceous or early Eocene (Nolan, 1935, p. 55, 56, 64). Overthrusting and transverse faulting corresponding to the third and fourth cycles in the Gold Hill district, Eocene to early Oligocene, are indicated in the area north of Cowboy Pass (Fig. 5, sections EF and GH) and possibly in the vicinity of the steep beds at the western ends of sections AB and IJ, and near the eastern end of IJ.

The folded Confusion Range contrasts markedly with the simpler, block-faulted House Range on the east, but toward the southeast, at the southern end of White Valley, there may be structural conformity between the rocks of the two ranges. No apparent indication of marginal, normal faulting exists in the northern Confusion Range, but the southeast side of the range drops steeply from nearly 8000 feet elevation to less than 4000 feet in White Valley, which might suggest block faulting. However, the dips in this area and the manner in which White Valley narrows toward the south suggest that a large, southward-plunging anticline may connect the House and Confusion ranges structurally actoss the southern end of White Valley.

CONCLUSIONS

The Confusion Range, the Gold Hill district 60 miles to the north, and the Oquirrh

Mountains 100 miles to the northeast seem to occupy the area of maximum sedimentation in a Permo-Carboniferous geosynclinal region (Nolan, 1935, p. 41–42). During the early Eocene (?), compression from the west produced the arcuate, folded Confusion-Conger Range complex. The shapes of the folds led to the following speculations. The approximate center of a circular arc constructed through the Confusion and Conger ranges lies 23 miles west in the Kern Mountains, Nevada. From the same center, three larger arcs may be constructed with 47-, 72-, and 112-mile radii. These are the House-Fish Springs, Beaver-Dugway, and Mineral-Pavant-Canyon-Tintic-Onaqui mountain arcs respectively (Butler 1920, Pl. 4). Somewhat inside the Beaver-Dugway arc and in parallel arrangement are the Thomas Range and Little Drum Mountains. Ranges due east of the center strike north. South of the center the ranges trend northeast, with the divergence from true north increasing southward, most rapidly in the smaller arcs; north of the center the ranges trend northwest with divergence from true north increasing northward, most rapidly in the smaller arcs. The smaller arcs are more perfect, but the others are not sufficiently offset by structural displacements to destroy the major lineation.

The great geological range and thickness of the Confusion Range stratigraphic section, the fossil wealth, good exposures, and the possible bearing of local structures on broader regional problems will stimulate interest in a detailed mapping of the area.

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KEY PERMIAN SECTION, CONFUSION RANGE, WESTERN UTAH

BY NORMAN D. NEWELL

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ABSTRACT

Approximately 10,000 feet of Permian strata, mainly of marine origin, and in some beds abundantly fossiliferous, is well exposed and readily accessible in the northern part of the Confusion Range, western Utah. Because of their strategic location between the better known sections of southern Nevada, southern Utah, and central Utah the exposures in the Confusion Range are of especial importance for the light they shed on Permian problems in the western United States. Pennsylvanian and Lower Permian limestones of undetermined total thickness are correlated with the similar Bird Spring formation of southern Nevada and with the Oquirrh formation of the Wasatch Mountains in central Utah. The Bird Spring limestone is overlain by 2500 feet of relatively unfossiliferous limy sandstones, impure limestones, and calcareous shales prevailingly of drab colors. Discontinuous lenses of red sandstone occur in the upper part. This unit tentatively is correlated with the Supai formation and associated clastics of the Grand Canyon region, although the lithologic facies is quite different. Approximately 2000 feet of massive limestone containing *Dictyoclostus ivesi* s.l. in the upper part is correlated with the Kaibab limestone of the Colorado Plateau. At the top of the Permian sequence is 4555 feet of richly fossiliferous interbedded cherty limestone and calcareous shale. The contained fauna is that of the Phosphoria formation of the middle and northern Rocky Mountains. There is no apparent intermingling of Kaibab and Phosphoria faunal types. The Permian succession is overlain with angular unconformity by red shales and interbedded limestones of the Lower Triassic. Silty red limestones some hundreds of feet above the base of the Triassic contain an abundance of *Meekoceras*. Interpretation of the succession in the Confusion Range confirms a discovery by Baker and Williams (1940) of Phosphoria strata directly above Kaibab equivalents in the Wasatch Mountains. It seems clear that the entire Phosphoria formation is younger than the Kaibab.

INTRODUCTION

Students of the Permian system have long been interested in the problem of the mutual time relations of the widespread Phosphoria formation of Idaho, Utah, Montana, and Wyoming, and the Kaibab formation of the Colorado Plateau area. Paleontological correlation has been impeded because the faunas of the two formations, which are as yet incompletely described, are markedly dissimilar to each other and to the better-known Permian faunas of West Texas.

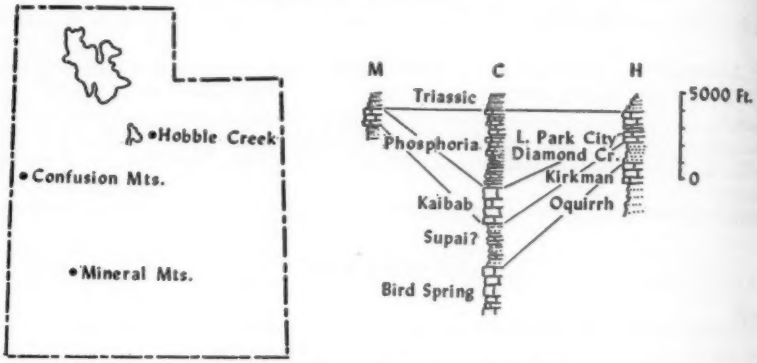

FIGURE 1.—*Sections of Permian rocks in Utah*
(Hobble Creek and Mineral Mountains sections after Baker and Williams, 1940.)

Paleontological evidence, although not yet summarized and not conclusive, suggests that both the Phosphoria and Kaibab faunas belong to the Word series of the standard Texas sequence.[1] Hence, the Kaibab and Phosphoria units probably do not differ greatly in geologic age.

Baker and Williams discovered what they believed to be Phosphoria limestones and shales overlying correlatives of the Kaibab formation, in the Wasatch Mountains near Provo, Utah (Baker and Williams, 1940; Baker, 1947). The most complete sequence there is found along Hobble Creek (Fig. 1). They used local names for the successive lithic units found there in the Pennsylvanian and Permian. The sequence along Hobble Creek is so strikingly different from rocks of the same age a few miles to the north that detailed correlations over comparatively short distances are quite difficult. According to Baker and Williams the most complete sequence is found within a thrust mass. Consequently, the rocks along Hobble Creek may have been displaced from a deeper part of the Cordilleran geosyncline to the west. Baker and Williams discovered typical Phosphoria fossils in the Upper Park City limestone. Especially diagnostic are *Punctospirifer pulcher* (Meek) and *Neospirifer pseudocameratus* (Girty). In the Lower Park City limestone they found a typical guide to the

[1] Dr. G. Arthur Cooper (personal communication) regards the brachiopods of the Kaibab formation as indicative of Word rather than of Leonard age as held by many workers. Also, *see* Longwell and Dunbar (1936) and Miller and Cline (1934) for evidence bearing on the age of the two formations.

Kaibab fauna, *Dictyoclostus ivesi* (Newberry) s.l. Underlying the Park City formation, equivalent to the Kaibab and Phosphoria divisions, Baker and Williams described an enormous succession of Permian and Pennsylvanian rocks which they have named, in descending order, Diamond Creek sandstone, Kirkman limestone, and Oquirrh formation. Baker and Williams note that Bissell reported the fusuline genus *Pseudoschwagerina* from the upper part of the Oquirrh formation. Baker (1947) indicates that the upper 9000 feet or more of the Oquirrh formation may belong to the Lower Permian (Wolfcampian). He cites identification of the fusuline genera *Schwagerina* and *Pseudoschwagerina* identified by L. G. Henbest. The succeeding section comprising the Kirkman limestone, Diamond Creek sandstone, and Park City formation is about 8500 feet thick. Thus, the total thickness for the Permian system is about 17,500 feet along Hobble Creek. In May 1948, the writer examined this section with Mr. Robert Adlington of The American Museum of Natural History. In general, the findings confirmed those of Baker and Williams.

Since the Hobble Creek rocks may be allochthonous, perhaps having been shoved for a considerable distance to the east, Adlington and the writer examined some of the mountain ranges in western Utah and discovered an unusually instructive Permian sequence in the northern part of the Confusion Range, western Utah, near the Nevada border. Although the total thickness of the Permian does not here equal that of the Hobble Creek section, the rocks are well exposed, more readily accessible, and are much more abundantly fossiliferous than at Hobble Creek. Kaibab and Phosphoria equivalents are individually much thicker than in the Wasatch Range and presumably are more nearly complete.

Acknowledgments are made to The American Museum of Natural History and to Columbia University, both of which shared in the support of this study through appropriation of special funds.

PERMIAN STRATIGRAPHY IN THE CONFUSION RANGE

The Confusion Range consists of several north-south low mountain ridges between the House Range and the Nevada border. It is formed of a series of nearly parallel hogbacks, which in the northern part of the range are formed by resistant Pennsylvanian and Permian limestones. The observations here reported were made in the northern part of the range, in the west-central portion of the Fish Springs quadrangle, Utah. The area is conveniently reached by U. S. Highway 6, which crosses the Confusion Range at Cowboy Pass. Numerous automobile trails extend northward from the highway to various points in the northern part of the range. The lower part of the stratigraphic sequence is best seen by following a dirt road through Indian Pass near Benchmark 5970 (Fish Springs quadrangle). The upper part of the section is readily accessible by following a dirt road to the north from Highway 6, near Benchmark 4848 about 6 miles east of Cowboy Pass. About 5 miles north of the highway a left fork in the road leads up into the hills for about 3½ miles. Eastward from Hill 7200 the Phosphoria formation crops out in excellent display for several miles.

The late Paleozoic beds in this area lie in simple stratigraphic succession, and be-

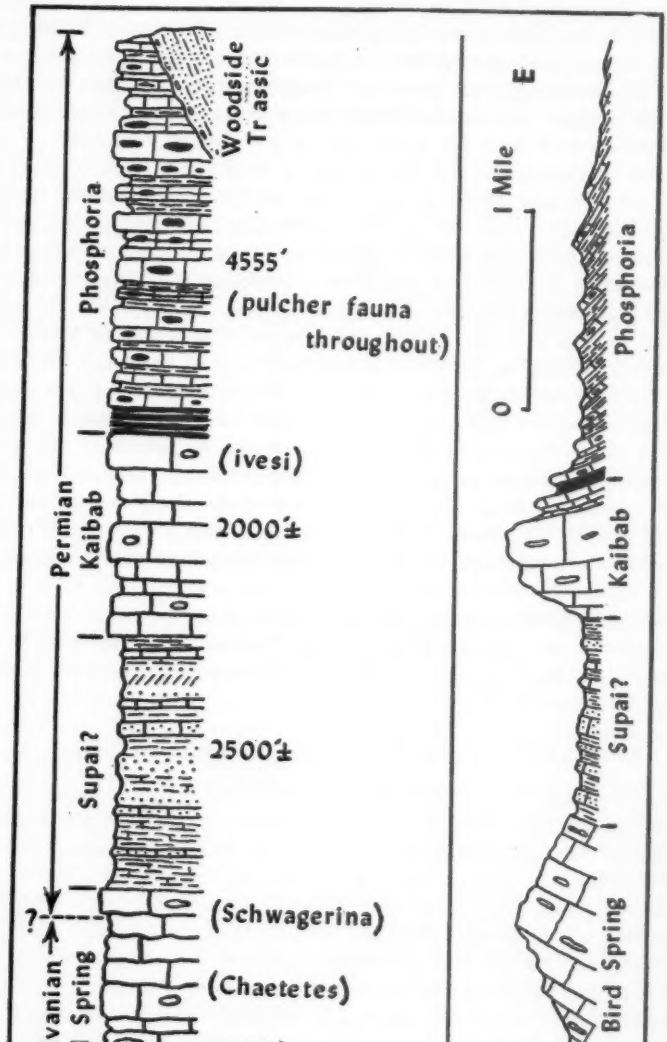

FIGURE 2.—*Succession of Permian rocks in the Confusion Range, western Utah*

cause of an arid climate there is very little soil. The oldest strata are on the west, and the youngest are on the east side of the range. The beds in the western part of the range are overturned, dipping as low as 45° or 50° W. Even casual inspection of the section, however, reveals that this dip rapidly steepens toward the axis of the range, where the strata are vertical. On the east flank of the range the strata rapidly flatten out toward the east where they assume dips as low as 30° before they disappear under the alluvial flats (Fig. 2).

Lower Triassic strata were recognized at a number of places in the outlying low hills on the east flank of the range, east-northeast of Benchmark 5970 at Indian Pass. In this area the Lower Triassic Woodside formation consists of several hundred feet, possibly more than 1000 feet, of alternating red shales and sandy limestones. They contain poorly preserved pelecypods. Red calcareous siltstones and ferruginous beds near the top of the exposed sequence contain an abundance of the lower Thaynes ceratite *Meekoceras*. Presumably, these ceratite-bearing beds lie above the top of the Woodside formation. The Triassic rocks rest locally on beds as old as the Kaibab limestone, but immediately north of the Triassic area thousands of feet of Permian rocks (Phosphoria formation) are preserved between the Triassic and the Kaibab limestone. Evidently there is considerable angularity between the Triassic and the Permian, although the relations along the contact were not studied in detail.

Permian section in the northern part of the Confusion Range, Western Utah

Phosphoria formation.—Limestones and limy shales, abundantly fossiliferous, containing several species of productids, spiriferoids, and a variety of bryozoans. The following forms are encountered at almost every horizon through the sequence: *"Productus" multistriatus, Waagenoconcha montpelierensis, Avonia subhorrida, Neospirifer pseudocameratus, Punctospirifer pulcher*, and *Composita mira*. Section measured with jacob staff.

Bed number		*Feet*
13.	Limestone, platy, gray, and interbedded limy shale, very cherty, abundant brachiopods and bryozoans, rather poorly silicified; uppermost beds dip gently eastward below the valley alluvium; exposed portion about	1000
12.	Limestone, light buff, fine, relatively unfossiliferous, and interbedded shaly limestone, with nodules of brown chert, top beds form crest of scarp	225
11.	Limestone, light brown, very cherty, abundant silicified brachipods and bryozoans, top bed makes scarp	230
10.	Limestone, gray, fine, with irregular brown nodules of chert, relatively unfossiliferous, very platy, with some shaly beds, forms scarp	120
9.	Shale, platy, buff and thin beds of gray limestone with brown chert and abundance of silicified brachiopods	1010
8.	Limestone, drab, rough, with abundant brown chert nodules and productids	45
7.	Limestone, gray, even, with brown chert nodules and some interbedded yellowish limy shale, contains abundant productids	215
6.	Limestone, dark gray, full of brown chert nodules and productids	95
5.	Limestone, gray, irregular, full of brown nodular chert, relatively unfossiliferous	150
4.	Mainly covered, otherwise similar to bed 3	300
3.	Limestone, ocher and gray, cherty, very fossiliferous, abundant productids	400
2.	Limestone and black shale, irregular, rough, brown, cherty, unfossiliferous	500
1.	Limestone, poorly shown, and shale, platy, bituminous	265
	Total Phosphoria	4555
Kaibab limestone.—	Limestone, cherty, crab to dark gray, relatively unfossiliferous but contains large *Dictyoclostus ivesi*, s.l. near top, forms main hogback ridge along the axis of the northern Confusion Range, relatively massive, hardly any shale; estimated at	2000
Supai equivalents.—	Shale, gray and buff, calcareous, and interbedded unfossiliferous sandy gray limestone, with a few beds of lenticular, hard, gray, calcareous sandstone. In upper part of sequence lenticular red, fine sandstone, entire sequence probably of marine origin; estimated at	2500

Bird Spring limestone.—Throughout the northern part of the Confusion Range overturned toward the east. Well exposed for the most part, but lower portion, of unknown thickness, covered by alluvium on west side of the range. About 2600 feet exposed, sparingly fossiliferous throughout. The formation consists of:

Limestone, massive, drab, cherty at a number of horizons, with poorly silicified brachiopods and corals usually associated with the chert bands. Large fusulinids belonging to the genus *Schwagerina* were collected at horizons 145 feet and 265 feet below the top of the formation. *Omphalotrochus* and *Waagenophyllum* collected 145 feet below top of formation. Hemispherical masses of Lower-Middle Pennsylvanian *Chaetetes* occur about 950 feet below top of formation. Negligible amounts of limy shale occur at a few horizons. Exposed part of the formation estimated at 2600 feet.

SUMMARY

The Permian sequence in the northern part of the Confusion Range appears to be unusually complete as compared with the Permian of better-known adjoining areas to the south and east. The strata are very fossiliferous. These facts, together with the convenient accessibility of the outcrops, make the Confusion Range section unusually important for an understanding of the Permian stratigraphy of the Nevada-Utah area. Additional sections in the Permian were sought in eastern Nevada, but no comparable sequences were found.

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